Indian Head Division
Naval Surface Warfare Center
Indian Head, MD 20640-5035

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SUMMARY OF TECHNICAL SUPPORT FOR *SEAWOLF* SHOCK TEST: POTENTIAL IMPACT ON MARINE-MAMMAL HEARING

Jean A. Goertner
Indian Head Division, Naval Surface Warfare Center

Delbert L. Lehto
Epoch Engineering, Inc.

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Jean A. Goertner, Indian Head Division, Naval Surface Warfare Center
Delbert L. Lehto, Epoch Engineering, Inc.

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13. ABSTRACT *(Maximum 200 words)*

This report documents a study performed in support of the SSN 21 (*Seawolf*) shock-test program. The purpose was twofold: (1) to develop a more efficient method for calculating potential acoustic damage to marine-mammal hearing from underwater explosions, and (2) to perform calculations specifically for use in preparing the *Seawolf* environmental impact statement. The most meaningful criterion for determining acoustic safe ranges would be one based on measurements of temporary threshold shift (TTS) in sea mammals exposed to underwater detonations. Because there are no existing data applicable to definition of such a criterion, an interim acoustic-energy limit, based on human in-air data, was developed for use in predicting the acoustic impact on the *Seawolf* detonations. Evidence indicates that this limit is very conservative. Therefore, until reliable measurements have been made of TTS that is directly attributable to exposure of marine mammals to sound produced by underwater explosions, this interim criterion should be used only for defining ranges for "acoustic discomfort" or annoyance.

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FOREWORD

This report documents a study performed in support of compilation of the environmental impact statement (EIS) for the SSN 21 (*Seawolf*) shock test. The purpose of this study was twofold: (1) to develop a more efficient method for calculating potential acoustic damage to marine-mammal hearing from underwater explosions and (2) to perform calculations specifically for the *Seawolf* EIS. The Naval Surface Warfare Center (NSWC), Indian Head Division (IHDIV), Code 460, was funded to perform the work described herein by NSWC, Carderock Division, Codes 622 and 3131, under the following: (1) APPR/SUB AA1771611.8224, Task Area 72, Element SCN, FRN 29510, (2) APPR/SUB AA97X4930.NH1C, FRN 99983, and (3) APPR/SUB AA1751319.H5YP, Task Area F1946, Element 64561N, FRN 35084.

The authors wish to acknowledge the assistance provided by Robert Thrun and Joel B. Gaspin of NSWC/IHDIV/Code 460, as well as the support of George A. Young of Epoch Engineering, Inc. and Thomas E. Farley of NSWC/IHDIV/Code 460 in carrying out this task.

Joel B. Gaspin for
Robert M. Barash
Manager, Weapon Effectiveness Branch

Approved by:

Thomas E. Farley
Thomas E. Farley
Director, Explosion Damage Division

Released by:

W. H. King
William H. King
Acting Head, Underwater Warheads Technology
and Development Department

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INTRODUCTION

An underwater explosion produces pressure pulses that have the potential for damaging the hearing of sea mammals that are too close to the explosion. Criteria for use in determining hearing-safe ranges have been developed for sea mammals exposed to underwater detonation of 10,000-lb charges.

Investigators with expertise in underwater-explosion acoustics and experts in marine-mammal hearing have agreed that acoustic-safety criteria for mammals exposed to underwater noise should be based on the amount of acoustic energy that impinges on the mammal ear.

Hearing threshold, which varies with frequency, is the quietest sound that can be heard. Hearing safety limits lie considerably above the hearing threshold. The most conservative safety limit is the highest sound level that causes no temporary threshold shift (TTS). A danger limit is the lowest sound level that causes permanent threshold shift (PTS), which is hearing loss.

The most meaningful criterion for determining acoustic safe ranges for sea mammals would be one that is based on measurements of TTS resulting from exposure to underwater noise. For underwater detonations such criteria should be species-specific and based on TTS measured for mammals exposed to underwater explosions.

The following summarizes the rationale and assumptions on which the environmental-impact predictions for *Seawolf* (SSN 21) are based. Appendices A, B, C and D present a detailed discussion of the development of the methodology and criteria.

METHODOLOGY

Hearing thresholds for odontocetes and pinnipeds exposed to pure tones (i.e., sine waves) of at least one-second duration have been measured. An exhaustive search has revealed no available hearing safety data (TTS or PTS) for any sea mammals.[1] Therefore, other methods must be used to estimate the potential for acoustic damage.

There are data for human underwater tolerance limits (levels that are uncomfortable but cause no TTS). Some measurements were made on hooded divers exposed to underwater explosions.[2] Unfortunately, these data could not be used because we have no information on the amount of attenuation provided by the hoods.

Data obtained from unhooded humans immersed in water and exposed to brief pure tones were used, augmented by human in-air data, to construct an underwater hearing-safety limit for marine mammals. This limit was then applied to define a very conservative safe range for exposure to an underwater detonation of a 10,000-lb explosive charge.

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[1] Richardson, W. J, Greene, C. R., Malme, C. I. and Thomson, D. H., *Marine Mammals and Noise*, Academic Press, Inc., San Diego, CA, 1995.

[2] Wright, H. C., Davidson, W. M. and Silvester, H. G., *The Effects of Underwater Explosions on Shallow Water Divers Submerged in 100 Feet of Water*, Medical Research Council, Royal Naval Personnel Research Committee, RNP 50/639, UWB 21, RNPL 4/50, October 1950.

HUMAN HEARING UNDER WATER

One study on humans measured threshold shift after 15 minutes' exposure, both in air and under water, to a 3,500-Hz pure tone.[3] Because these data are for long exposure to pure tones, they are not directly applicable to our problem.

Figure 1 shows underwater hearing thresholds for odontocetes and humans.[4,5] The solid human-data curve does not have the same slope as the odontocete data, but it lies very close at 1,500 Hz, the frequency at which human tolerance level was also measured.

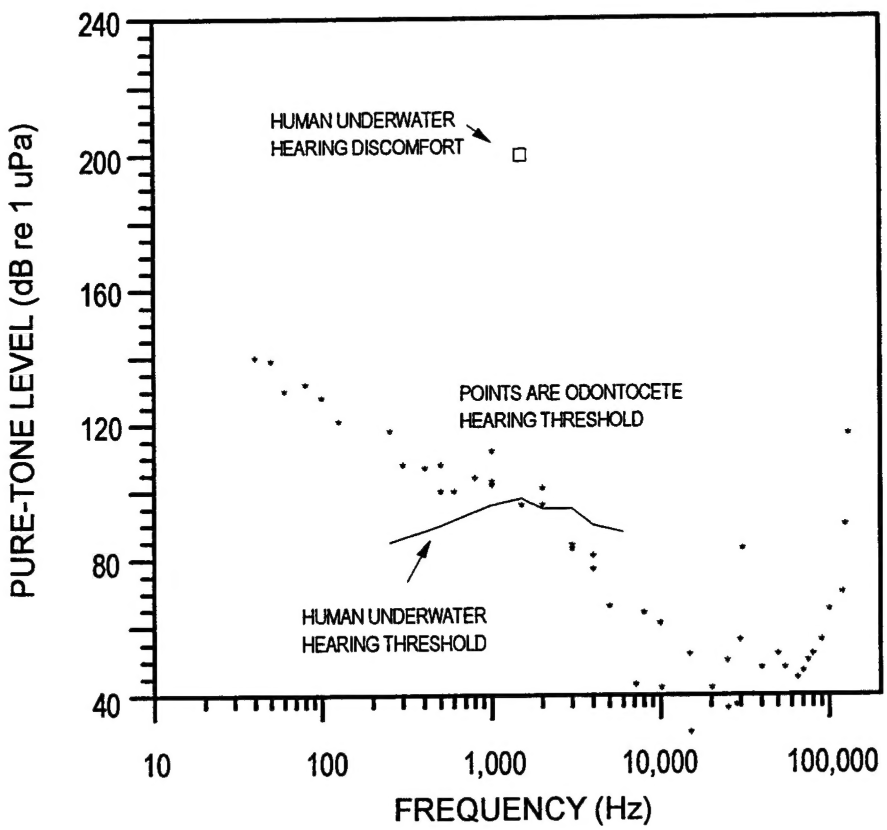

FIGURE 1. ODONTOCETE AND HUMAN UNDERWATER HEARING THRESHOLDS

[3] Smith, P. F., Howard, R., Harris, M. and Waterman, D., *Underwater Hearing in Man: II. A Comparison of Temporary Threshold Shifts Induced by 3500 Hz Tones in Air and Underwater*, U.S. Naval Submarine Medical Center, Groton, CT, Report Number 608, 15 Jan 1970

[4] Richardson, W. J. et al, *Effects of Noise on Marine Mammals*, LGL Ecological Research Associates, Inc., Bryan, TX, done for Mineral Management Service, Herndon, VA, PB91-168914, Feb 91 [p. 180]

[5] Montague, W. E., and Strickland, J. F., *Sensitivity of the Water-Immersed Ear to High- and Low-Level Tones*, J. Acoust. Soc. Am. 33(10):1376-1381 (1961)

The plotted square is a hearing-tolerance level found by exposing hoodless divers to one-second-duration 1,500-Hz tones from a source directly in front of them.[3] The tones were gradually increased in level by 1 dB until the divers wanted to go no further. An in-air hearing test conducted within 5 minutes of the underwater test showed no hearing damage and no TTS. The plotted square is useful as a conservative (no TTS) limit for sea mammals, but a limit is needed at more than one frequency. To obtain this limit, data on human hearing in air were used.

There are human data in air for threshold, discomfort, and pain.[6,7] Figure 2 shows these levels. In Figure 3 the in-air data have been shifted by 95 dB, so that the human in-air threshold matches the human underwater threshold near 1,500 Hz. The discomfort and pain curves have been shifted by the same amount. The shifted "human pain" and "human discomfort" curves lie just above the measured-in-water human-tolerance data point (the square); this gave us confidence that use of the in-air data was not completely unreasonable. The dotted line was then drawn through the square and parallel to the upper in-air curves. This line could be used as a no-TTS, human safety limit for continuous tones.

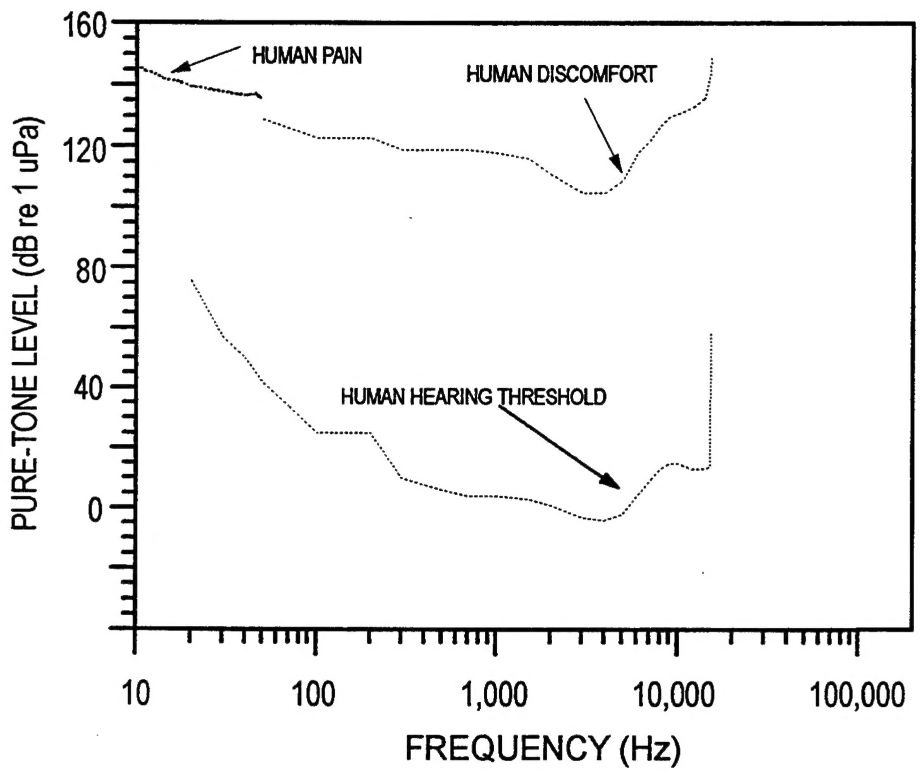

FIGURE 2. HUMAN IN-AIR HEARING THRESHOLD, DISCOMFORT, AND PAIN LEVELS

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[6] Everest, F. A., *The Master Handbook of Acoustics*, 3rd ed. (Tab Books, McGraw-Hill, N. Y., 1994) [p. 43]

[7] Edge, P. M., Jr., and Mayes, W. H., *Description of Langley Low-Frequency Noise Facility and Study of Human Response to Noise Frequencies Below 50 cps*, NASA TN D-3204, 1966.

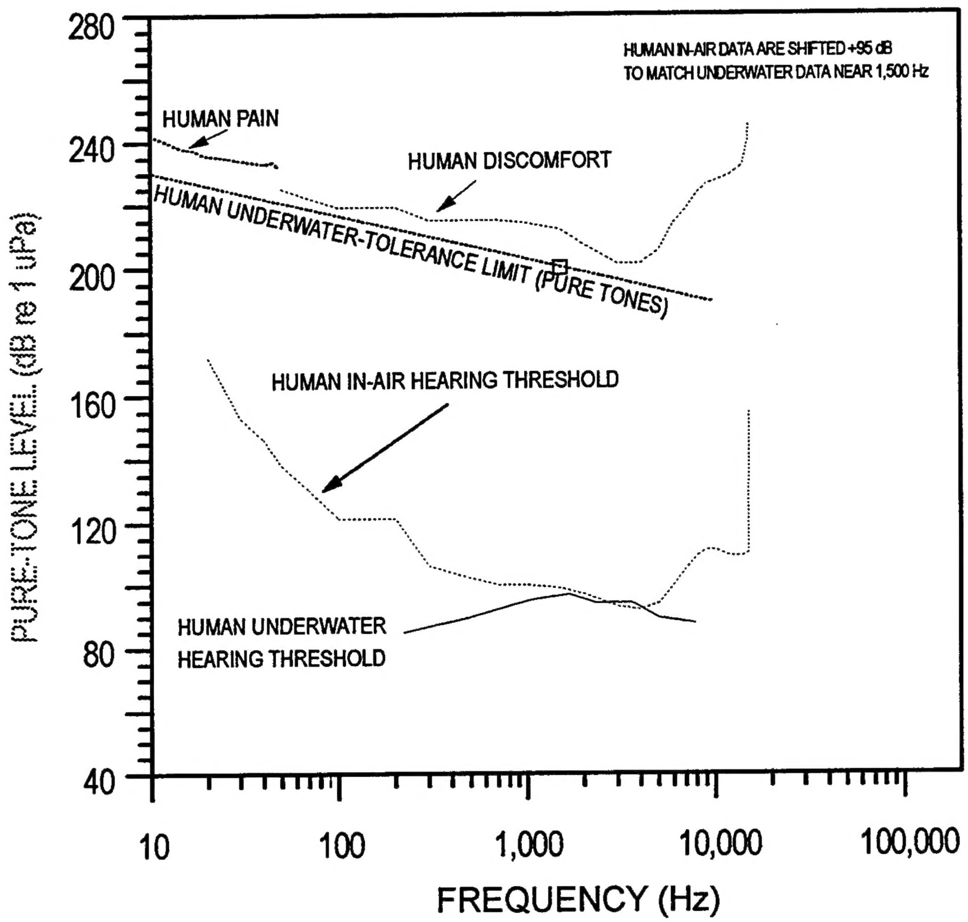

FIGURE 3. HUMAN IN-AIR LIMITS SHIFTED TO UNDERWATER

Because human and dolphin hearing are comparable at their respective frequencies of best hearing, it was suggested that the method of shifting the human in-air data be modified. The dolphin frequency range reflects their specialized use of high-frequency sound. Therefore, to extrapolate from human to dolphin hearing mechanics, we have shifted the human auditory curve up in frequency by a factor of ten to match the range of the dolphin hearing curve. The level of the human in-air curve (see Figure 2) has also been shifted up by 45 dB to match the odontocete threshold level. The discomfort and pain curves have been shifted by like amounts. Since we now can no longer make use of the single human underwater-tolerance data point (the square in Figure 3), we proposed the straight line that skims the bottom of the human-discomfort curve in Figure 4 as the revised safety limit for sea-mammal hearing.

The line in Figure 4 is 30 dB lower than the very conservative human underwater-tolerance limit presented in Figure 3. An additional indication of how conservative this line is for humans is the circle plotted in Figure 4. Humans were exposed to a 3,500-Hz pure tone for 15 minutes. Two minutes after exposure, a TTS of 30 dB (no damage) was measured.[3]

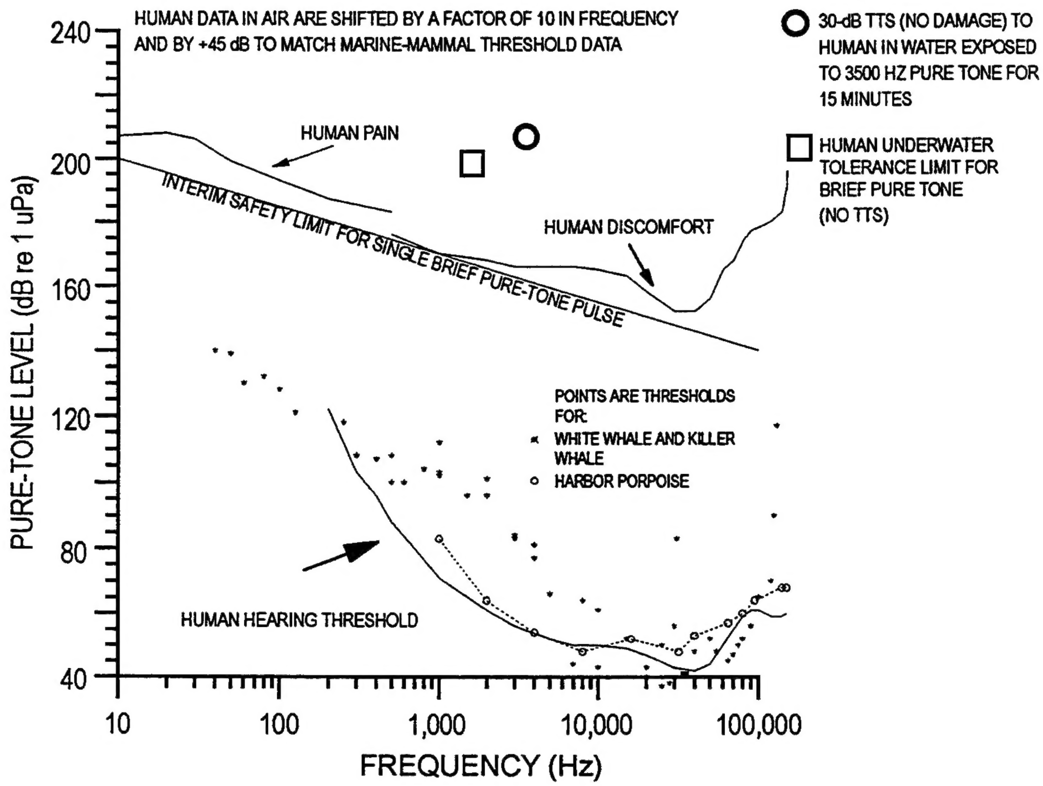

FIGURE 4. INTERIM MARINE-MAMMAL SAFETY LIMIT FOR PURE BRIEF TONES: BASED ON SHIFTED, HUMAN IN-AIR DATA

To convert the above limit to energy, so that it can be compared with explosion output, we made use of the integration time of the ear. For humans, the integration time is about 0.1 to 0.2 seconds. Because we could find no clear value for the integration time of marine mammals, we have used 0.1 second, which appears conservative for porpoises,[8] to define an underwater hearing-safety limit for humans, which was originally proposed as a "sea-mammal hearing-safety limit."

Figure 5 shows how the criterion can be applied to the energy field calculated for a particular set of ocean conditions. The new "interim safety limit" (Figure 4) has been converted to energy and is plotted as a dotted line. Considering the basis for its derivation, we believe this should be viewed as a criterion for acoustic discomfort or annoyance.

[8] Johnson, C. S., *Relation between Absolute Threshold and Duration-of-tone Pulses in the Bottlenosed Porpoise*, J. Acoust. Soc. Am. 43 (4) 757-763, 1968.

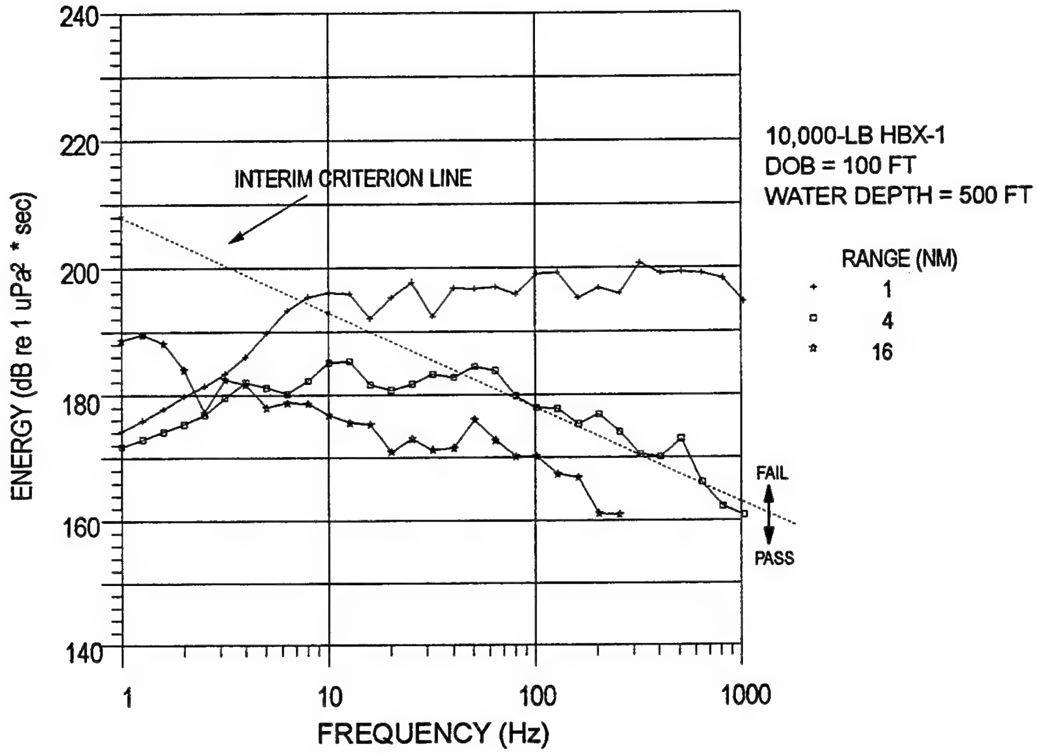

FIGURE 5. EXAMPLE OF APPLICATION OF INTERIM HEARING-SAFETY LIMIT

Although audiograms have been measured for some odontocetes, the only information available for baleen whales is based on observation and anecdotal information.[9,10] Figure 6 shows representative hearing ranges for ondontocetes and baleen whales.[11] Since these whales regularly and repeatedly produce source levels of 180 to 185 dB in the lower frequencies of this range without deafening themselves, the criterion we have employed should be conservative for them also.

[9] Ketten, D. R., "The Marine Mammal Ear: Specializations for Aquatic Audition and Echolocation" p 717-750 in *The Biology of Hearing*, Springer-Verlag, Berlin, 1991.

[10] Ketten, D., "The Cetacean Ear: Form, Frequency, and Evolution" p 53-75 in *Marine Mammal Sensory Systems*, Plenum, New York, 1992.

[11] Ketten, D. et al, Marine Mammal Bio-Acoustics Short Course, Orlando, FL, 1995.

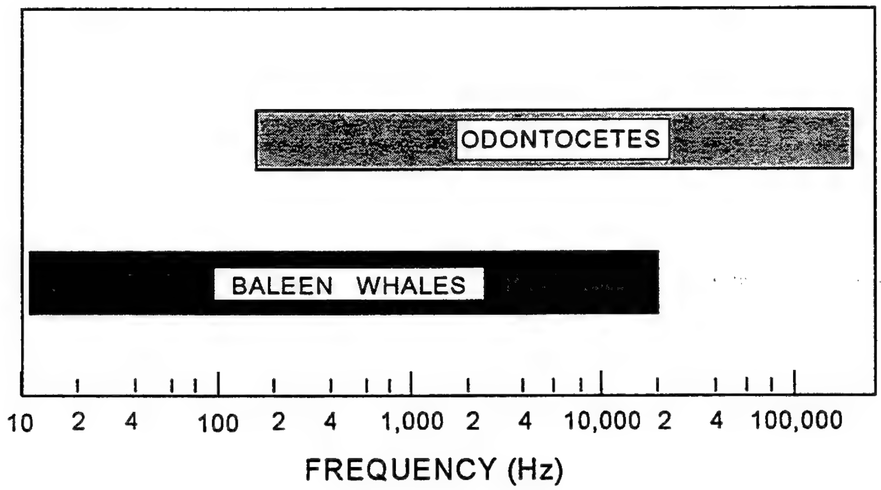

FIGURE 6. REPRESENTATIVE HEARING RANGES FOR LARGE WHALES AND DOLPHINS

METHOD OF CALCULATION

The pulse train from a relatively shallow underwater explosion consists of a direct shock wave closely followed by companion surface-reflected and bottom-reflected pulses of opposite sign. For a 10,000-lb charge, a 100- or 200-ft charge depth is "relatively shallow."

The procedure for dealing with explosion pulses is to:

(1) Calculate the pressure-versus-time (p-t) waveform
(2) Obtain the spectrum as energy/Hz
(3) Integrate the spectrum to get energy/(1/3-octave band)
(4) Compare this energy directly with the safety limit.

The p-t waveform is calculated with Version 5.0 of the REFMS computer code.[12] A water sound-speed profile and a bottom profile are required. A charge size and depth are chosen. Then, for a given range, waveforms are calculated at the desired depths (in this case, selected mammal locations). Energy spectra are obtained from the p-t waveforms by standard methods.

For the *Seawolf* calculations, we employed sound-speed profiles measured in the two proposed test areas. To be conservative, we have used the complete calculated pulse train even if it contains pulses separated by more than 0.1 second. (It could be argued that pulses separated by more than 0.1 seconds allow the ear to recover, and so the pulses should be considered individually.)

[12] Britt, J. R., Eubanks, R. J., and Lumsden, M. G., *Underwater Shock Wave Reflection and Refraction in Deep and Shallow Water: Volume I - A User's Manual for the REFMS Code (Version 4.0)*; Science Applications International Corporation, P.O. Box 469, St. Joseph, LA 71366-0469, DNA-TR-91-15-V1, June 1991.

DISCUSSION OF RESULTS

Using the limited number of archival sound-speed profiles available for the two proposed test sites, calculations were made of the acoustic environment to which sea mammals might be exposed as a result of detonating 10,000-lb charges for the *Seawolf* shock test. The mammal depth was varied from 50 to 400 feet (in 500 feet of water). Plots of energy (in 1/3-octave bands) were made for ranges from one nautical mile (nm) to as much as 6 or 8 nm. The interim criterion line has been plotted along with the energy level as a function of mammal depth at the indicated range.

In Appendix E, Figures E-1 through E-6 show selected plots for the Norfolk test area; Figures E-7 to E-11 are results for the Mayport area. Although the water column in the Mayport area seems to have a rather stable velocity structure, there are very few archival profiles available. Profiles in the Norfolk area are quite variable. In the latter region, vortices from the Gulf Stream can cause wild swings in both sound-speed and current profiles in as little as 24 hours. Since the Mayport test area is also adjacent to the Gulf Stream, one might expect variability similar to that observed near Norfolk.

Although we do not have energy plots at 6 and 8 nm for all the cases shown in Appendix E, we can generalize to some extent about the calculations made using the archival profiles from these two areas. For the same profile, the 1/3-octave-band energy levels tend to drop by 5 to 10 dB going from 1 to 2 nm, another 5-10 dB going from 2 to 4 nm, another 5 dB from 4 to 6 nm, and probably another 5 dB going from 6 to 8 nm. In addition, the dropoff with range becomes faster as the frequency increases.

For both areas, archival profiles can give us only an indication of the variability one might expect during a given time period. The cases shown are for profiles most representative of the variability to be expected from April to July in the two areas.

Generally, the interim safety limit, which we consider to be extremely conservative insofar as acoustic damage to the mammal ear, indicates a probable range for discomfort or annoyance from 4 to 6 nm. The trend is for the "safe" range to become shorter later in the summer and into early fall. This is a function of the increasing temperature of the water.

There is a variation with mammal depth, however. In general, the deeper the mammal, the lower the explosion-noise level at range. In some cases, the calculated "safe" range for a mammal at 100 feet is greater than 6 nm, even though all other depths indicate a range within 4 to 6 miles. When we make calculations for a depth of 50 feet, however, the curve tends to drop below the 100-foot curve (see Figures E-6 and E-11).

While most of the calculations were performed for frequencies up to 1 kHz, a few have been extended to 10 kHz and beyond (see Figures E-4 to E-6 and Figures E-9 to E-11). Because acoustic attenuation at 10 kHz is significantly high and increases rapidly with frequency, the explosion energy falls off much more rapidly above this frequency. This is of most interest for the odontocetes at ranges of 6 nm and beyond, because their frequencies of best hearing tend to be in the 30 to 40 kHz region.

Although the April profiles show portions of some of the curves above the criterion at 6 nm, these tend to be in the frequency range below 100 Hz, which is probably below the frequency of best hearing for the baleen whales. The parts of these curves that lie above the criterion between 100 and 1,000 Hz (probably the range of best hearing for the baleen whales) are at or below the levels at which these animals regularly and repeatedly produce vocalizations that do not deafen them.

CONCLUSIONS AND RECOMMENDATIONS

There are no existing data applicable to the definition of a meaningful criterion for potential auditory injury to marine mammals exposed to underwater explosions. The interim acoustic-energy limit developed for use in predicting the acoustic impact of the *Seawolf* detonations is based on human in-air data. Evidence that indicates how conservative this limit is for people has been provided by studies made with humans exposed to brief pure tones underwater (no TTS) and humans exposed to pure tones for 15 minutes underwater (30 dB TTS: no damage).

Until reliable measurements have been made of temporary threshold shift, TTS, that is directly attributable to exposure of marine mammals to sound from underwater explosions, this interim criterion should be used only for defining ranges for "acoustic discomfort" or annoyance.

One must keep in mind that the actual acoustic field on any given day will depend on the sound-velocity structure at that time and on the actual bottom sediment and structure in the area. Calculations made using archival information provide only an estimate of what one should expect. Actual *in situ* profile measurements and calculations made during the test series must be used to guide those who will be responsible for monitoring and mitigation.

APPENDIX A

ORIGINAL PROPOSAL FOR SAFE RANGE FOR MAMMAL HEARING

Technical Note DLL-1995-6
by
D. L. Lehto
June 5, 1995

PRELIMINARY

DLL-1995-6

PROPOSED HEARING-SAFE RANGE FOR SEA MAMMALS IN THE VICINITY OF A LARGE UNDERWATER EXPLOSION

D. L. Lehto

Technical Note

June 5, 1995

Abstract: A hearing-safe range of one nautical mile is recommended for sea mammals in the vicinity of a 10,000 lb explosion.

Work done by: D. L. Lehto, Consultant
102 Lillian Lane
Silver Spring, MD 20904-1115
(301) 989-2592

Working thru: Epoch Engineering, Inc.
806 West Diamond Ave, Suite 200
Gaithersburg, MD 20878
(301) 670-6600
Attn: J. M. P. Wright, Jr.

Sponsored by: NSWC/Carderock Division, Code 622
APPR/SUB AA 1771611.8224
Task Area 72, Element SCN, FRN 29510

Unclassified

PRELIMINARY

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FIGURES

INTRODUCTION

An underwater explosion produces pressure pulses that can potentially damage the hearing of sea mammals that are too close to the explosion. The purpose of this report is to propose a "hearing-safe" range of 1 nautical mile for a 10,000 lb explosion.

MARINE MAMMAL HEARING

The hearing threshold is the quietest sound that can be heard. It varies with frequency. The hearing threshold for odontocetes and pinnipeds is well known; Figure 1 shows some data for odontocetes (Ref. 1). The data for pinnipeds are quite similar. These data are for pure tones (i.e., sine waves) of at least 1 second duration.

Hearing safety limits lie considerably above the hearing threshold. The most conservative safety limit is the highest sound level that causes no temporary threshold shift (TTS). The ear recovers from moderate TTS (e.g., 10 dB). A danger limit is the lowest sound level that causes permanent threshold shift (hearing loss). Unfortunately, there appear to be no hearing safety data (TTS or PTS) available for sea mammals.

There are data for human underwater tolerance limits (levels that are uncomfortable but cause no TTS). We will use the human underwater data, assisted by human in-air data, to construct a mammal underwater hearing safety limit. We will then use this limit to find a safe range for a large underwater explosion.

HUMAN HEARING UNDER WATER

The solid curve on Figure 1 shows human underwater threshold measurements from Ref. 2; the curve does not have the same slope as the whale data, but it lies very close to the whale data at 1500 Hz, where the tolerance level was also measured. (Some differences may be due to "shock mounting" of the inner ear in sea mammals (Ref. 3), which prevents hearing by bone conduction. Immersed land mammals have much bone conduction.)

The plotted square is a hearing tolerance level, found by exposing hoodless divers to 1-second duration 1500 Hz tones from a source directly in front of them (Ref. 2). The tones were gradually increased in level by 1 dB until the divers wanted to go no further. An in-air hearing test conducted within 5 minutes of the underwater test showed no TTS (temporary threshold shift); there was no hearing damage. The measured tolerance level was 174 dB re 20 uPa, which is 200 dB re 1 uPa (the usual underwater reference value).

The plotted square is useful as a conservative (no TTS) limit for sea mammals, but a limit is needed at more than one frequency. To obtain this limit, data on human hearing in air is used.

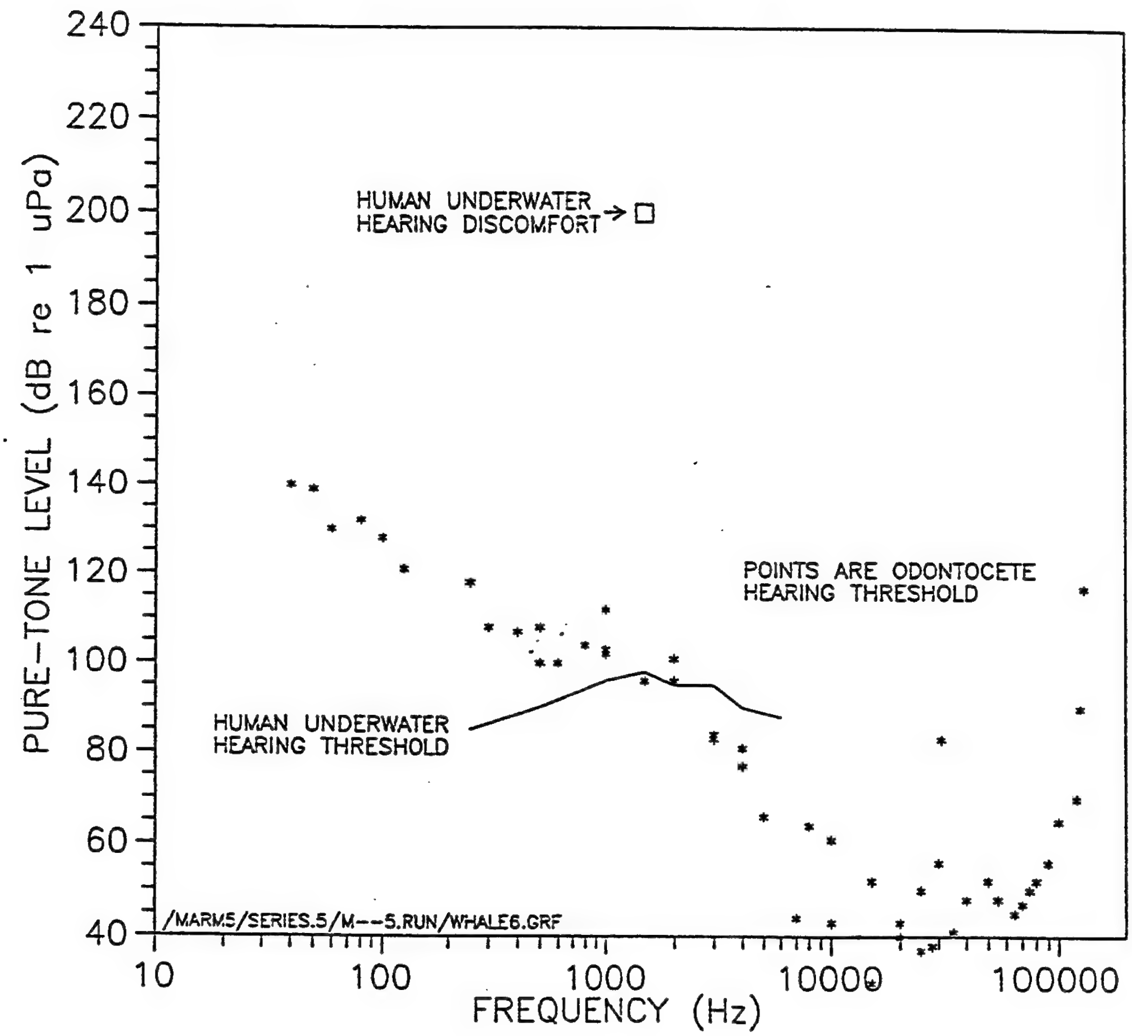


Fig. 1 — Odontocete and human underwater hearing thresholds

Refs. 5 and 6 give human data in air for threshold, discomfort and pain. In Fig. 2, we have shifted the air data by 100 dB so that the human threshold matches the odontocete threshold in the 100 to 1000 Hz range. The discomfort and pain curves have been shifted by the same amount. The shifted "human pain" and "human discomfort" curves lie just above the measured-in-water human tolerance data point (the square); this serves as a check on the use of the air data. The air data are now used to find the slope of a line thru the square. The resulting dashed line is then a safety limit for continuous tones. The equation of the dashed line is:

dB = 244.5 - 14 Log(Hz) [re 1 uPa; pure tones]

We need to convert this to energy so it can be compared with explosion output. Multiplying the square of pressure by a time gives energy (neglecting the [density*sound speed] term, as is customary in acoustics). A physiologically meaningful time is the integration time of the ear. A short tone does not sound as loud as a long tone of the same amplitude. For short tones, the ear responds to the total energy of the tone rather than to its amplitude. The tone duration below which which this effect occurs is the integration time of the ear.

For humans, the integration time is about 0.1 to 0.2 seconds. The dashed line on Fig. 3 shows the dB by which a short tone has to be increased to make it sound as loud as a long tone. Also shown are porpoise (Tursiops) data (Ref. 4); these do not give a clear value for the integration time, so we will use 0.1 seconds, which appears conservative for porpoises.

The energy received in 0.1 seconds may be obtained by subtracting 10 dB from the above equation (i.e., by multiplying P^2 by 0.1 second and using 1 uPa^2*s as the reference):

dB = 234.5 - 14 Log(Hz) [re 1 uPa^2*s; energy]

This is a human underwater hearing safety limit. We will use it as a "sea mammal hearing safety limit".

COMPARING PURE TONES WITH EXPLOSION PULSES

Everything said so far has been for pure tones and pulsed pure tones. We will use the properties of the ear to relate explosion pressure pulses to pure tone pulses. Hearing damage from loud noise is caused by damage to hair cells in the cochlea. A hair cell that bears the full brunt of a pure tone responds to only part of the energy of an explosion pulse: the energy of the pulse is spread out over a range of frequencies, most of which lie outside the hair cell response bandwidth of about 1/3 octave.

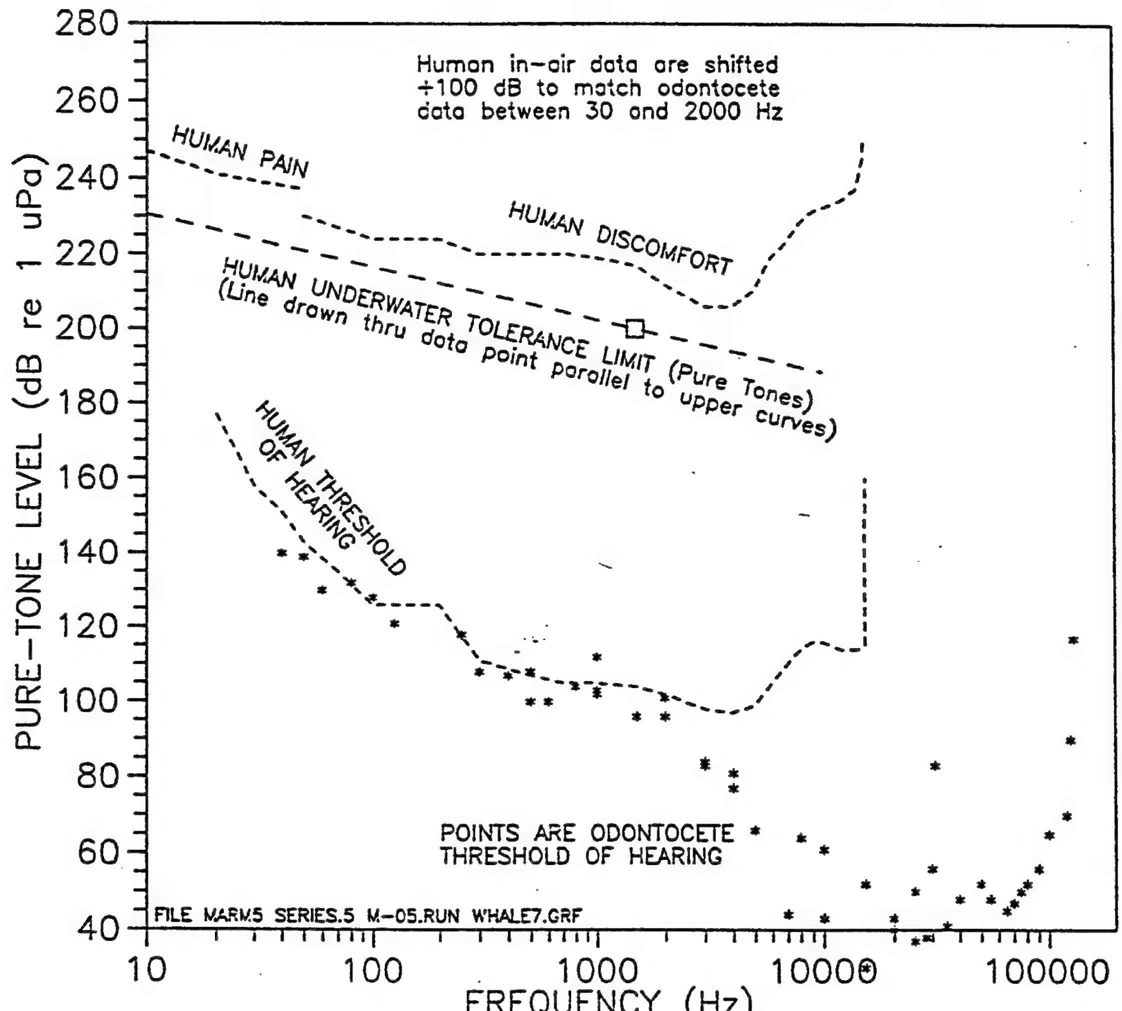


Fig. 2 – Human in-air limits shifted to match odontocete data: Setting slope of human underwater limit

PRELIMINARY

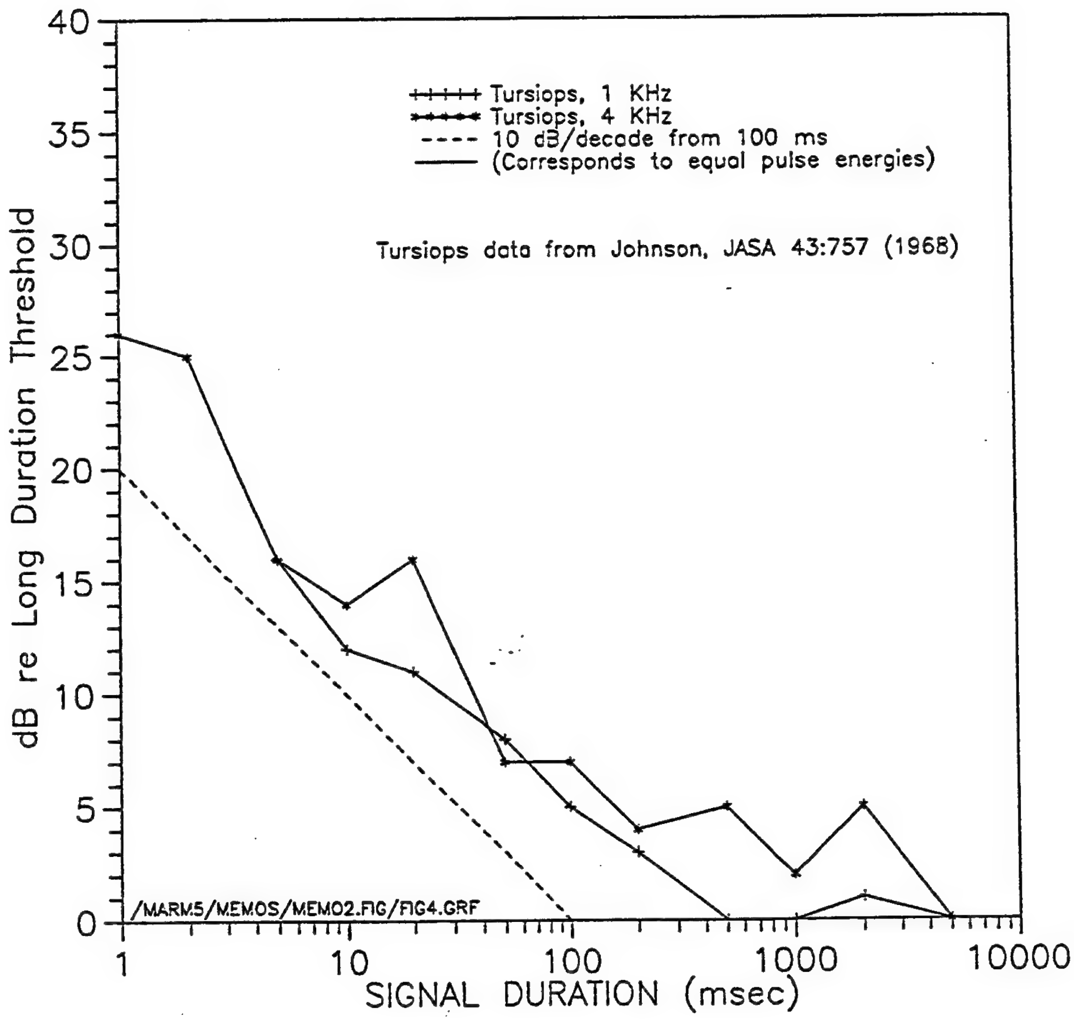


Fig. 3 — Hearing Threshold vs Signal Duration (Pure Tones)

PRELIMINARY

Our procedure for dealing with explosion pulses is to:
1) calculate the pressure vs time waveform;
2) obtain the spectrum as energy/Hz;
3) integrate the spectrum to get energy/(third-octave band);
4) compare this energy directly with the safety limit.

LARGE UNDERWATER EXPLOSIONS: THE PULSE TRAIN

The pulse train from a (relatively shallow) underwater explosion consists of pulses closely followed by companion surface-reflected pulses of opposite sign:

1) a direct pulse [D and S on Fig. 7p];
2) a bottom-reflected pulse [B and SB];
3) a bottom-to-surface reflected pulse [BS and SBS];
4) a pulse that propagates along the ocean bottom and radiates a wave into the water;
5) pulses that reflect from the bottom more than once. These contain less energy than pulses 1) thru 3); they are neglected here mainly because of problems in calculating accurately to late times. (Fig. 7p shows such a pulse at 0.41 s.)

When there is strong refraction, the direct pulse may be reduced or absent.

For a 10,000 lb charge, a 200 ft charge depth is "relatively shallow". The surface reflection arrives before the positive phase of the direct wave is completed.

METHOD OF CALCULATION

The pressure vs time waveform is calculated with the REFMS computer code (Ref. 7), Version 5.0. A water sound velocity profile and bottom profile are required; for these calculations the bottom is assumed to be a single infinitely thick layer of sand. A charge size and depth (usually 10,000 lb at 100 to 200 ft depth for shock tests) are chosen. A range is chosen and waveforms are calculated at the desired depths. Appendix A shows a comparison of REFMS results with an experimental waveform.

The spectra are obtained from the p-t waveforms by standard methods; the codes used are EXPRES for energy/Hz and BAND for integrating to energy/(third-octave band).

We conservatively use the as-calculated train even if it contains pulses separated by more than 0.1 seconds. (It could be argued that pulses separated by more than 0.1 seconds allow the ear to recover, so the pulses should be considered individually.)

Many calculations were done for various sound velocity profiles, bottom types, and ranges. A candidate safety range of 1 nautical mile (NM) was chosen; explosion energy spectra for 1 NM are compared here with the sea mammal hearing safety limit.

RESULTS FOR NORTHEAST PACIFIC SITE

The 10,000 lb charge is at a depth of 200 ft. The water depth is 3000 ft.

Three sound velocity profiles (Fig. 4) are considered:

A) Maximum
B) Mean
C) Minimum

Fig. 5p shows the p-t waveforms at a range of 1 NM and a depth of 500 ft. The direct wave (plotted at time zero) is influenced by refraction; the peak values are marked. The lowest peak, B, is for the SVP with steepest slope at the charge depth.

Note that the bottom-reflected waves (between 0.4 and 0.7 seconds) are influenced very little by the SVP. The range is only two times the water depth, so the bottom-reflected waves pass thru the upper layers at a large angle. The four bottom-reflected peaks are, in order of arrival:

1) bottom reflection (0.42 s);
2) surface-bottom reflection (0.47 s);
3) bottom-surface reflection (0.56 s);
4) surface-bottom-surface reflection (0.62 s).

Figure 5e shows that the spectra for all three SVP lie below the hearing safety limit.

RESULTS FOR KEY WEST SITE

The 10,000 lb charge is at a depth of 200 ft. The water depth is 1500 ft.

One mean deep-water velocity profile (Fig. 6) is considered.

Fig. 7p shows the p-t waveforms at a range of 1 NM and a depth of 500 ft.

Fig. 7e shows that the energy spectrum lies below the hearing safety limit.

RESULTS FOR NORFOLK-J SITE

These conditions are those of five tests conducted in the past. The 10,000 lb charge depth is 100 ft and the water depth is 300 ft.

Five sound velocity profiles (Fig. 8) are considered, one for each shot.

Figs. 9-13 show that the energy spectra lie below the hearing safety limit.

RESULTS FOR NORFOLK-S SITE

These conditions are for proposed tests east of Norfolk. The 10,000 lb charge depth is 100 ft and the water depth is 500 ft.

Five sound velocity profiles (Fig. 14) are considered. They are historical profiles extended from 300 ft to 500 ft depth using deeper-water data.

0) Iso-velocity water;
1) August historical extreme low
2) August historical extreme high
3) September historical extreme low
4) September historical extreme high

Pressure vs time and corresponding energy spectra for four gauge depths are shown in Figures 15-18. All the spectra lie below the safety limit.

CONCLUSION

For a 10,000 lb explosion at a depth between 100 and 200 ft, 1 NM appears to be a reasonable sea mammal hearing-safe range.

REFERENCES

(1) W. J. Richardson, et al, "Effects of Noise on Marine Mammals," LGL Ecological Research Associates, Inc., Bryan, TX, done for Mineral Management Service, Herndon, VA, PB91-168914, Feb 91 [p. 180]

(2) W. E. Montague & J. F. Strickland, "Sensitivity of the Water-Immersed Ear to High- and Low-Level Tones," J. Acoust. Soc. Am. 33(10):1376-1381 (1961)

(3) P. E. Purves & G. E. Pilleri, Echolocation in Whales and Dolphins (Academic Press, N. Y., 1983) [p. 10].

(4) C. S. Johnson, "Relation between Absolute Threshold and Duration-of-tone Pulses in the Bottlenosed Porpoise," J. Acoust. Soc. Am. 43 (4) 757-763 (1968)

(5) F. A. Everest, The Master Handbook of Acoustics, 3rd ed. (Tab Books, McGraw-Hill, N. Y., 1994) [p. 43]

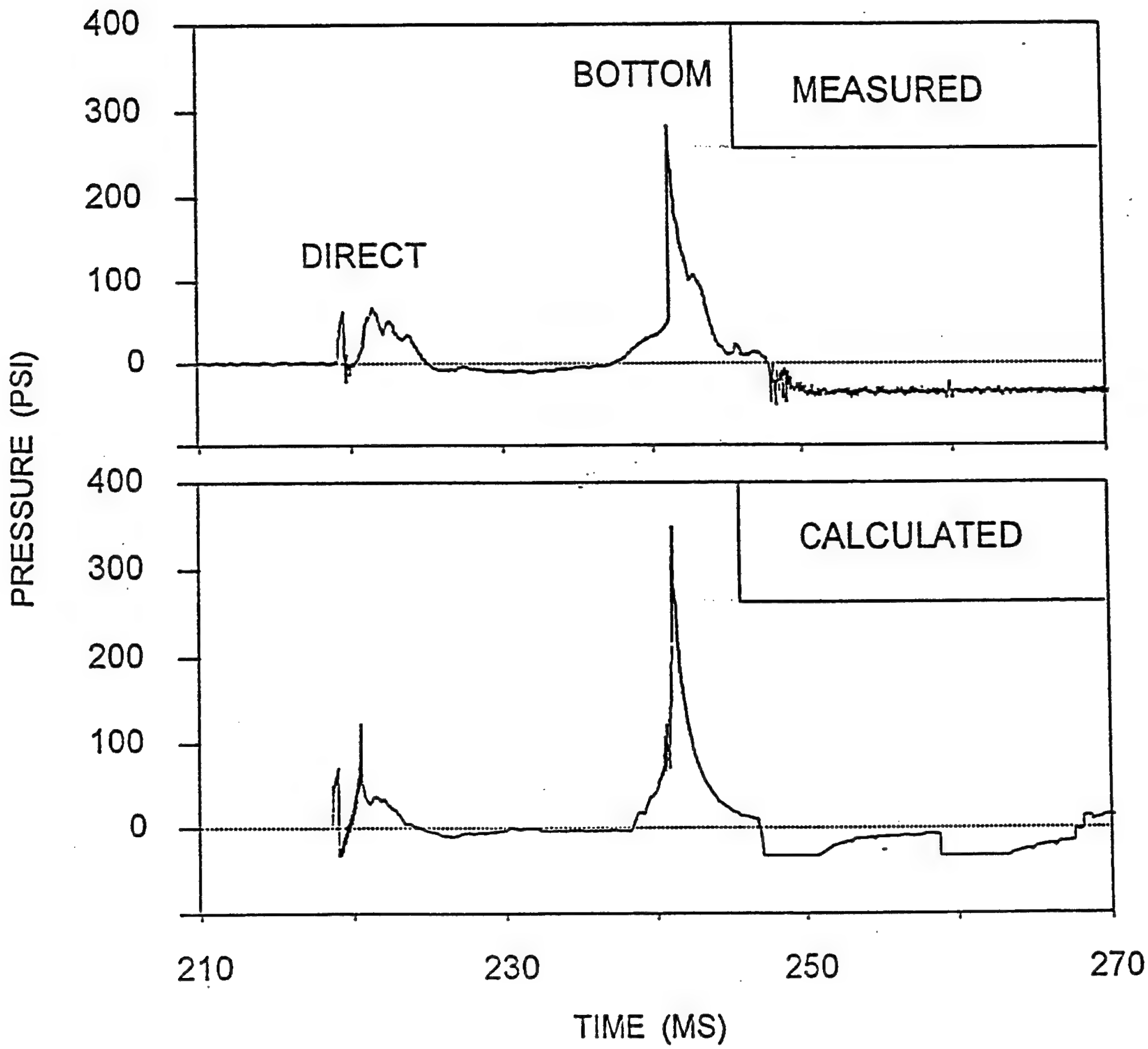
(6) P. M. Edge, Jr. & W. H. Mayes, "Description of Langley Low-Frequency Noise Facility and Study of Human Response to Noise Frequencies Below 50 cps," NASA TN D-3204, 1966.

(7) J. R. Britt, R. J. Eubanks & M. G. Lumsden, "Underwater Shock Wave Reflection and Refraction in Deep and Shallow Water: Volume I - A User's Manual for the REFMS Code (Version 4.0); Science Applications International Corporation, P.O. Box 469, St. Joseph, LA 71366-0469, DNA-TR-91-15-V1, June 1991. [The references in this report lead back to detailed documentation of the methods used and experimental verification.]

APPENDIX A - A Verification of REFMS

This figure shows a comparison of a REFMS calculation with experimental data. The conditions are:

Explosive weight	10,000 lb
Explosive depth	100 ft
Water depth	300 ft
Gauge range	1097 ft
Gauge depth	43 ft



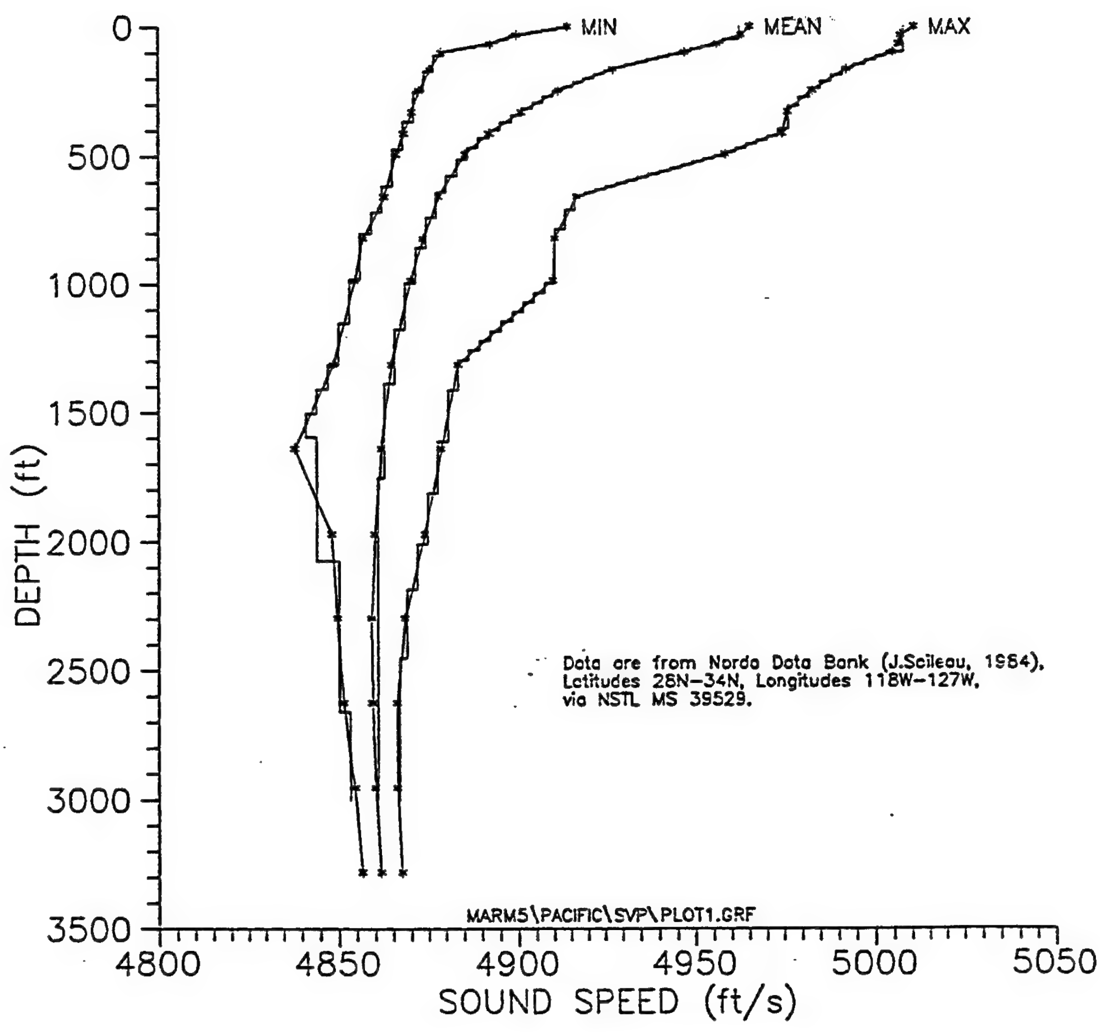


Fig. 4 – Pacific Site Sound Velocity Profiles

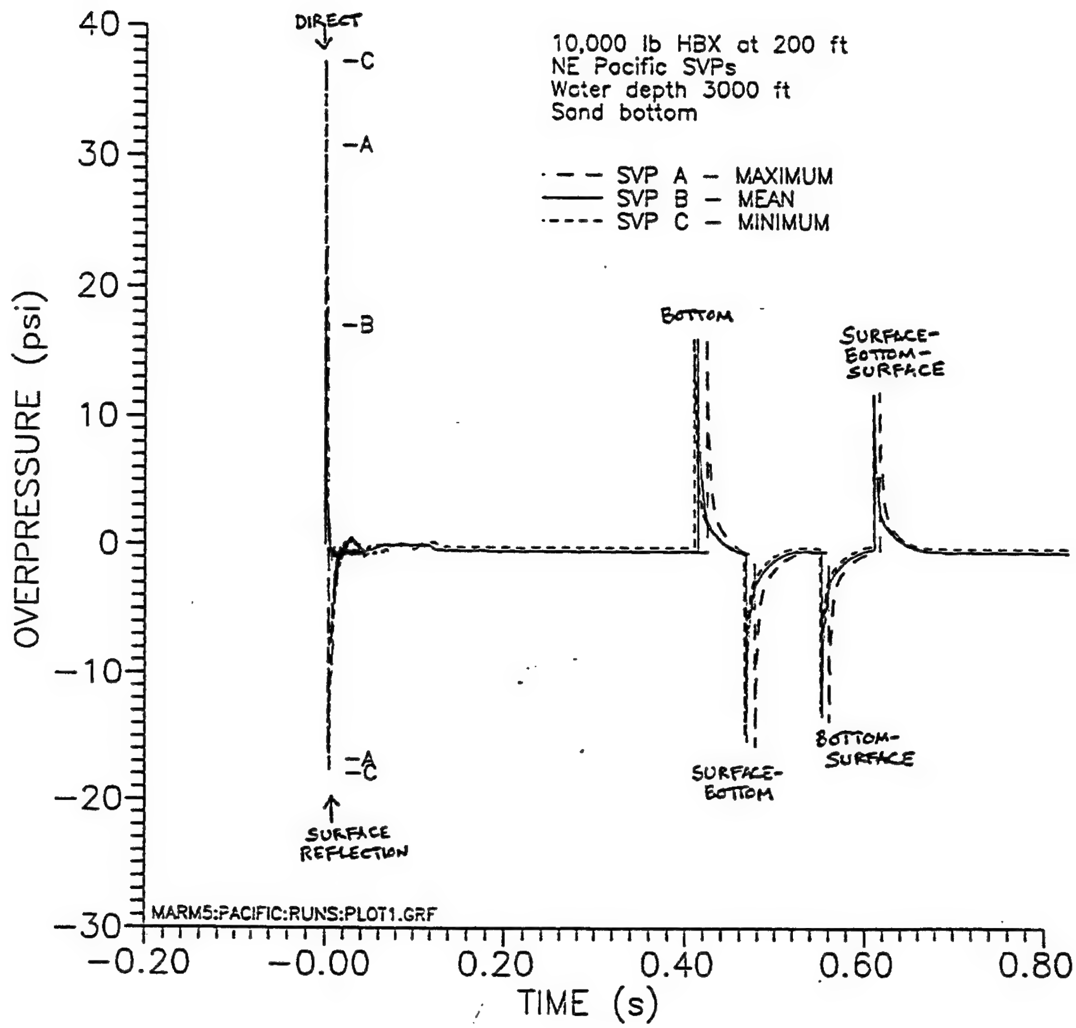


Fig. 5p – Pacific P vs T, Range 1 NM, Depth 500 ft

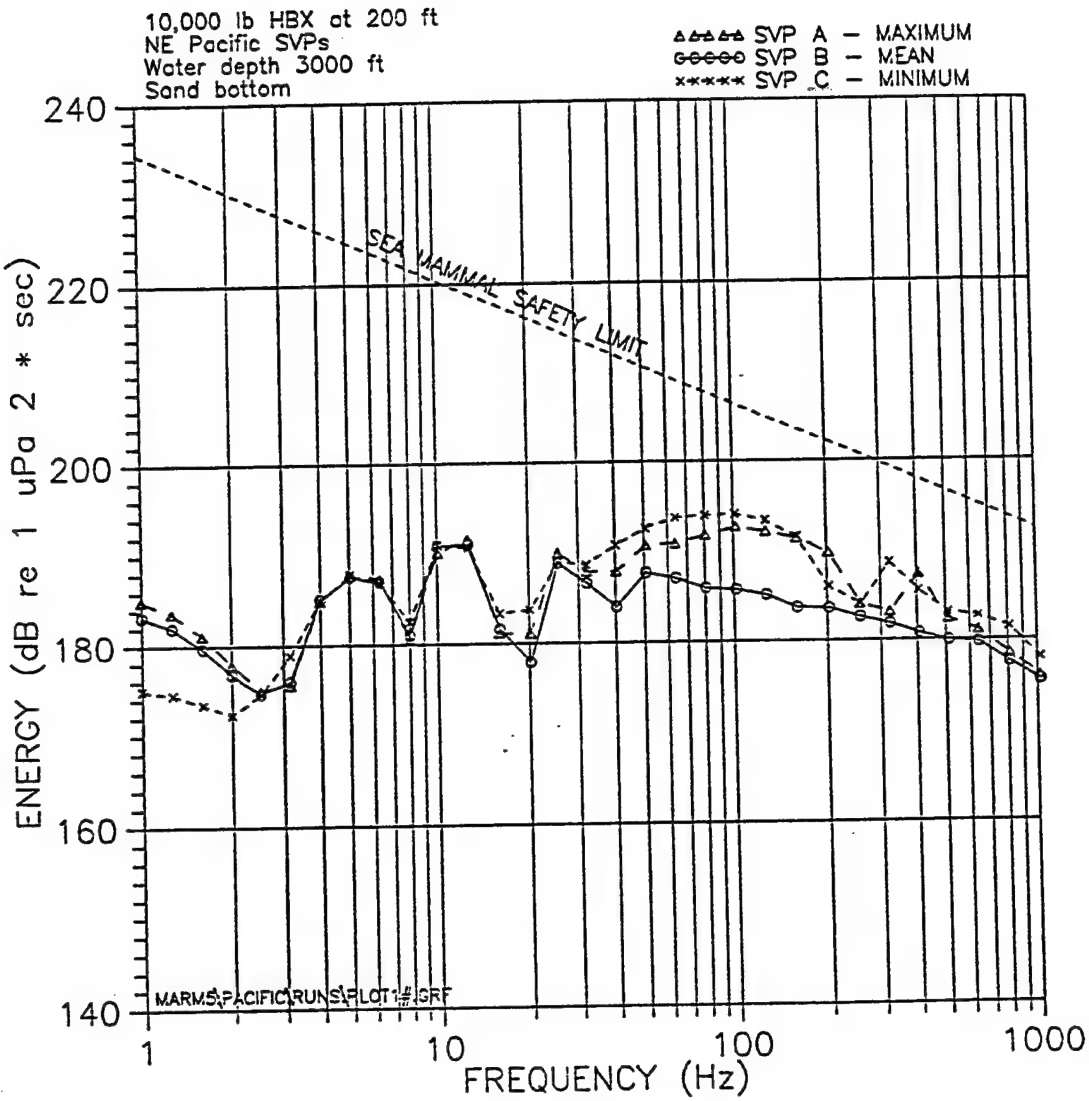


Fig. 5e – Pacific E vs F, Range 1 NM, Depth 500 ft

PRELIMINARY

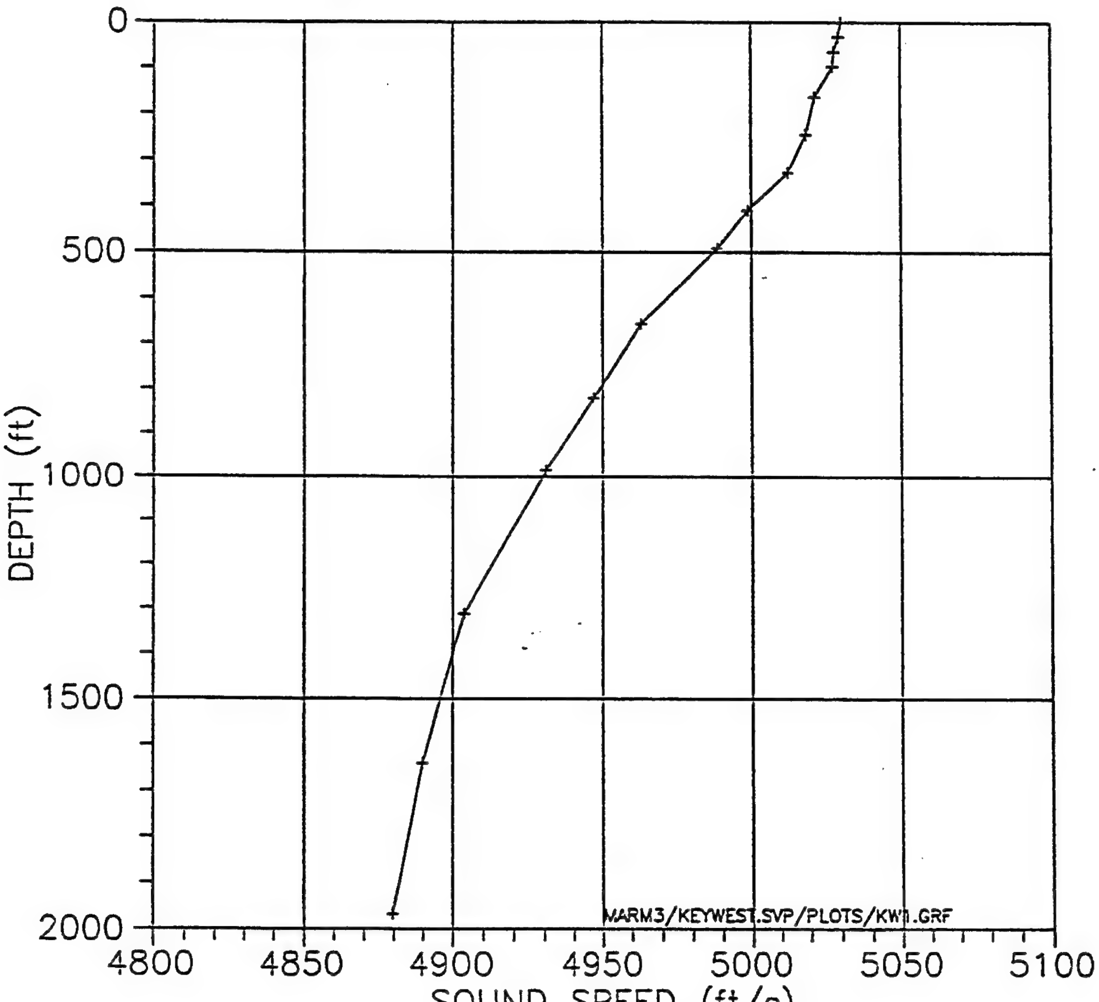


Fig. 6 - Key West Mean SVP

PRELIMINARY

PRELIMINARY

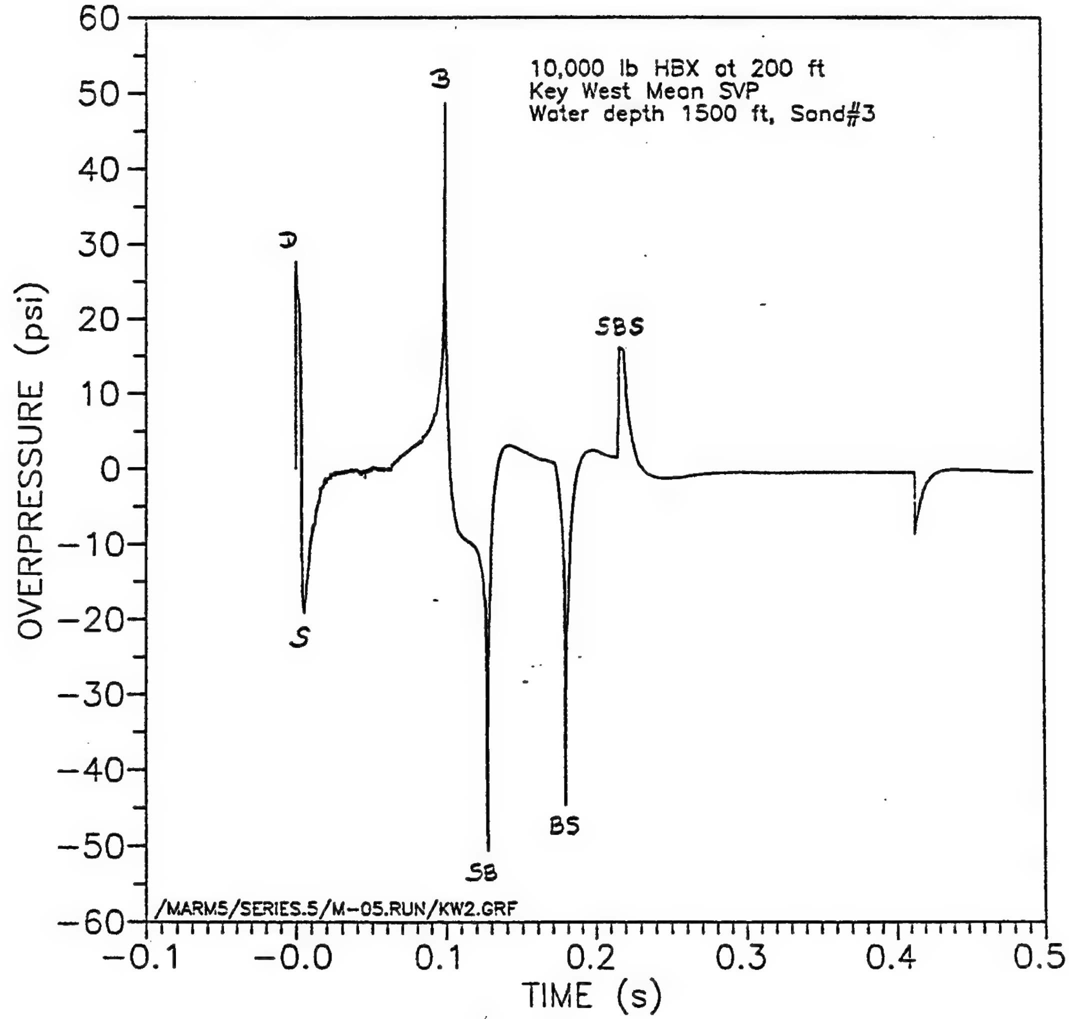


Fig. 7p – Key West P vs T at Range 1 NM, depth 500 ft

PRELIMINARY

PRELIMINARY

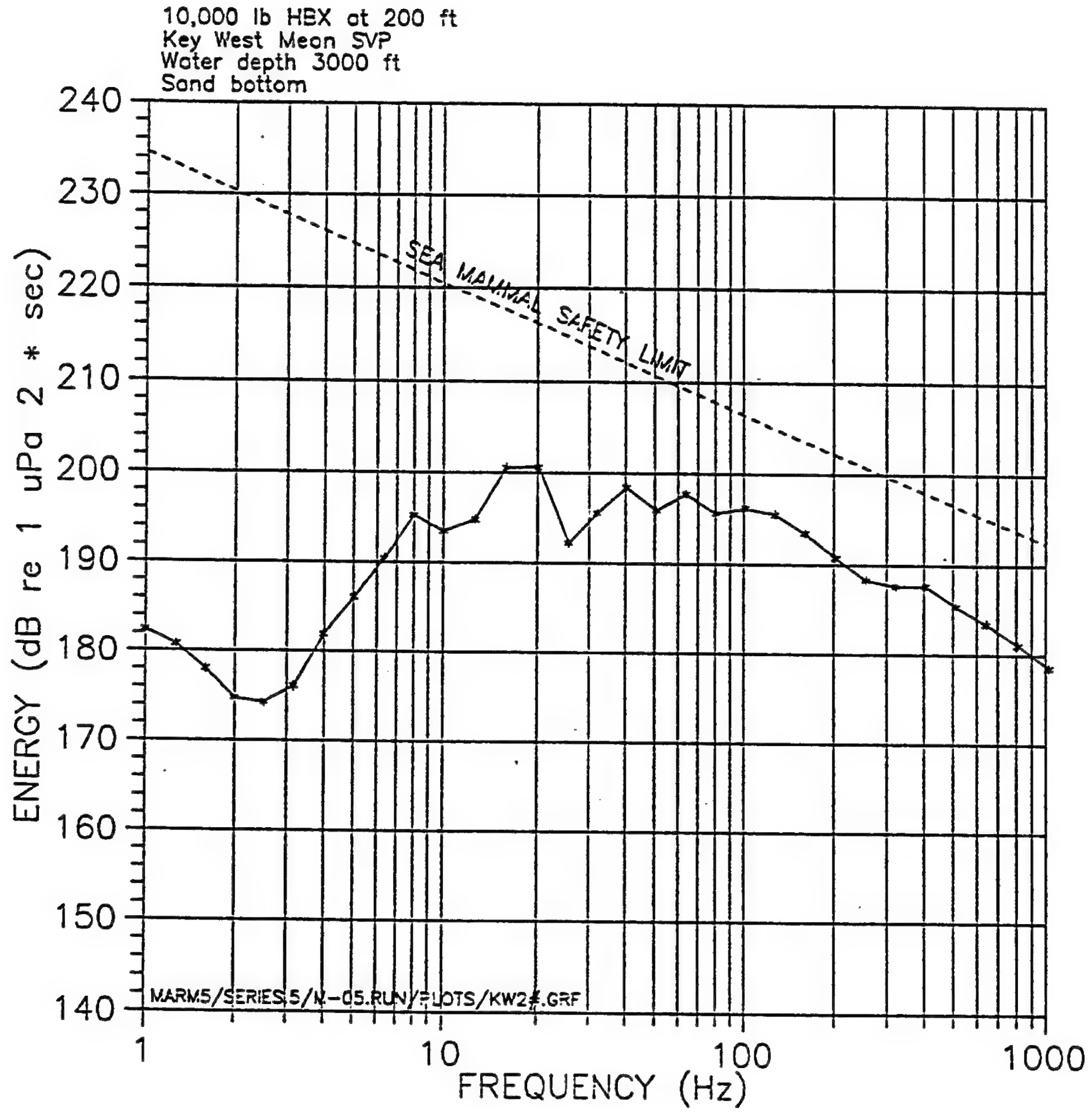


Fig. 7e – Key West E vs F at Range 1 NM, Depth 500 ft

PRELIMINARY

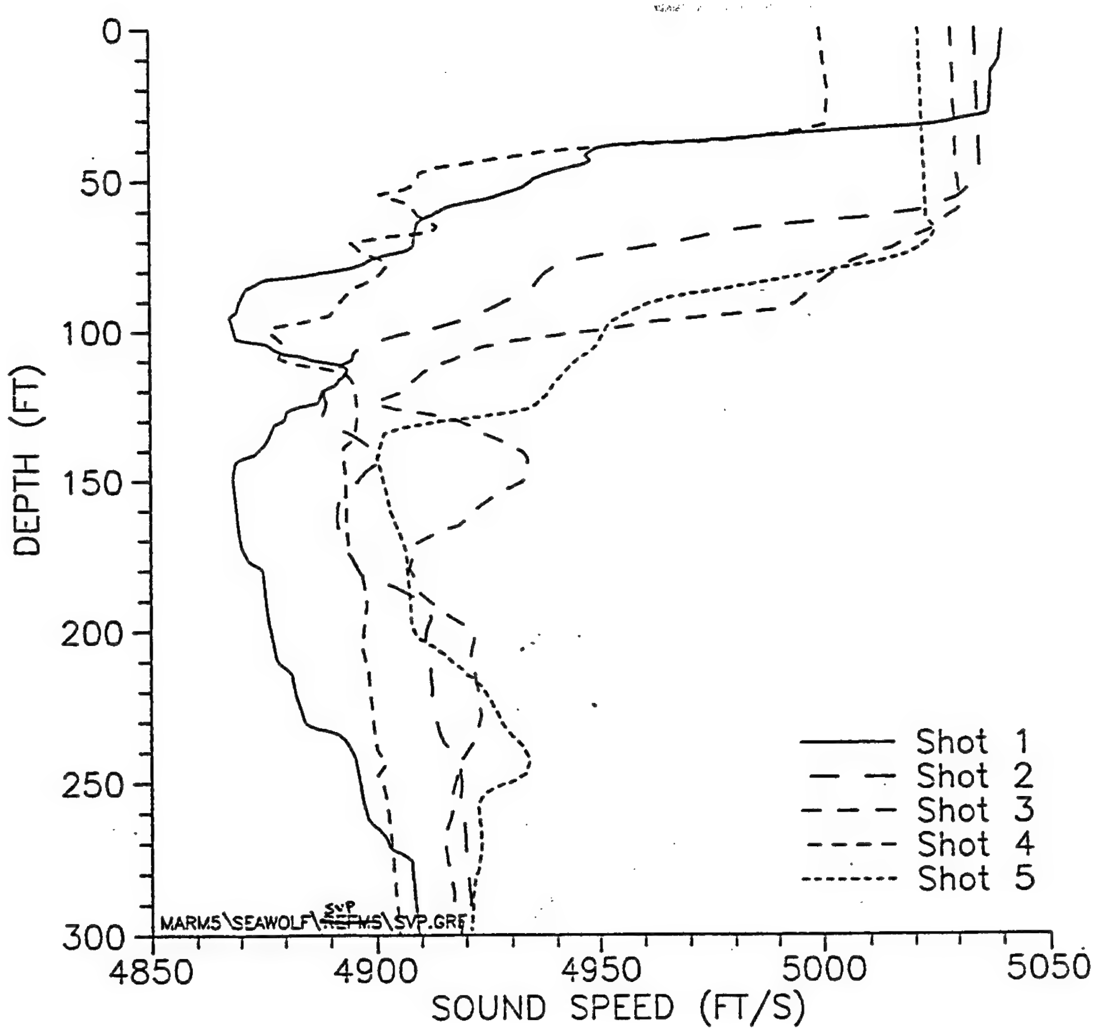


Fig. 8 – Norfolk–J Site SVPs, Shots 1–5

PRELIMINARY

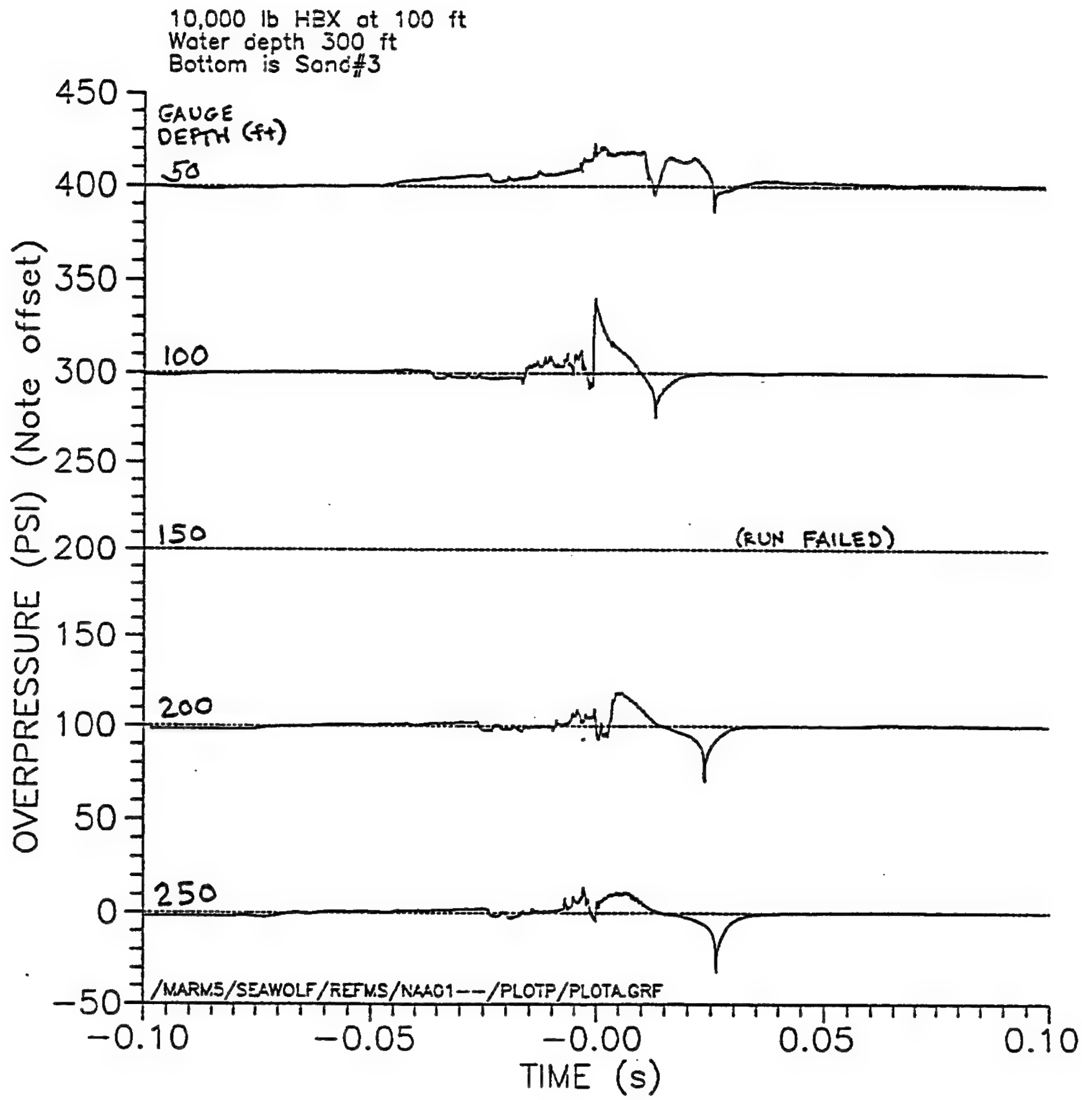


Fig. 9p − Norfolk−J P vs T, Shot 1, Range 1 NM, Depths vary

PRELIMINARY

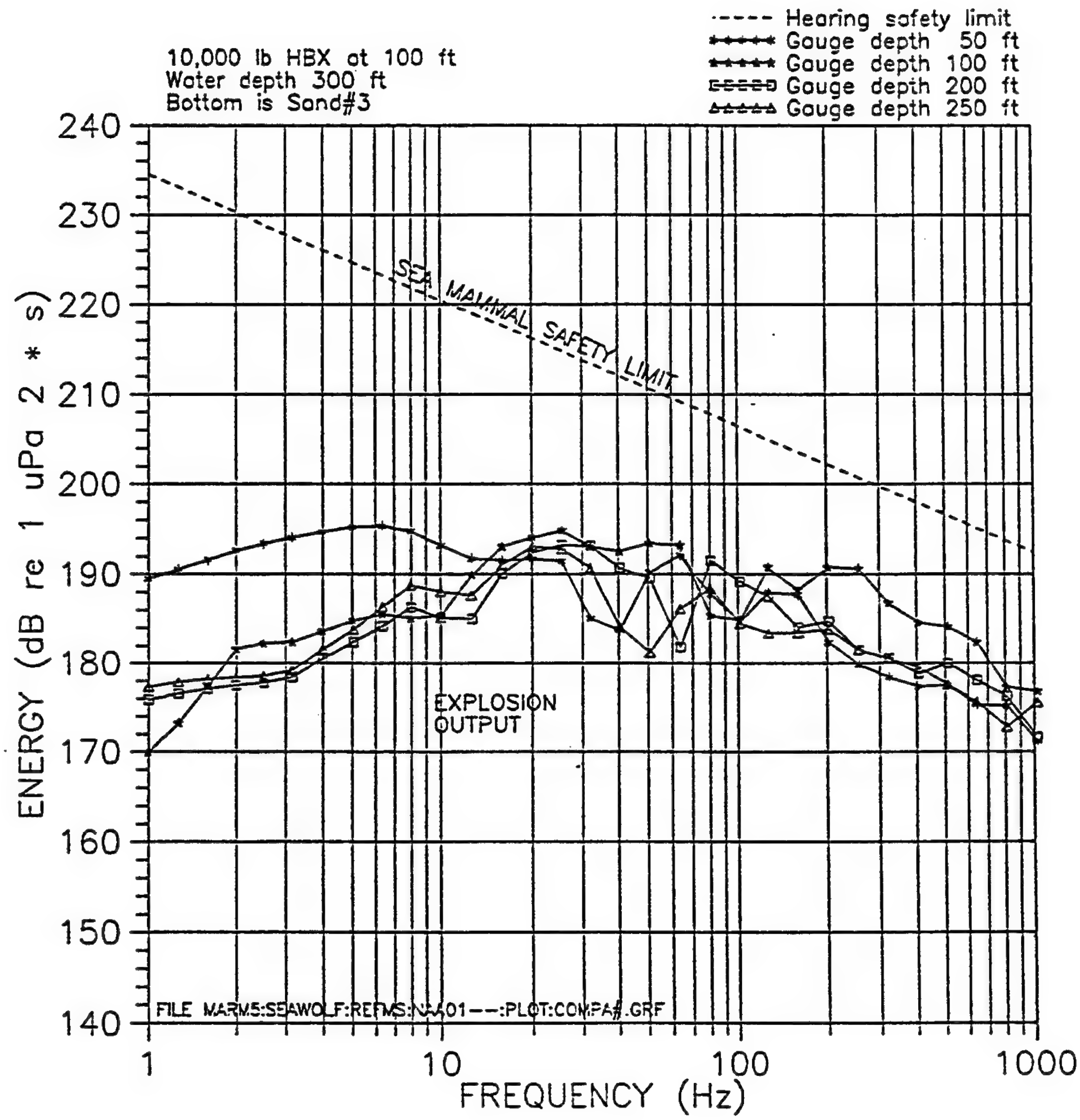


Fig. 9e — Norfolk—J E vs F, Shot 1, Range 1 nmi, Depths vary

PRELIMINARY

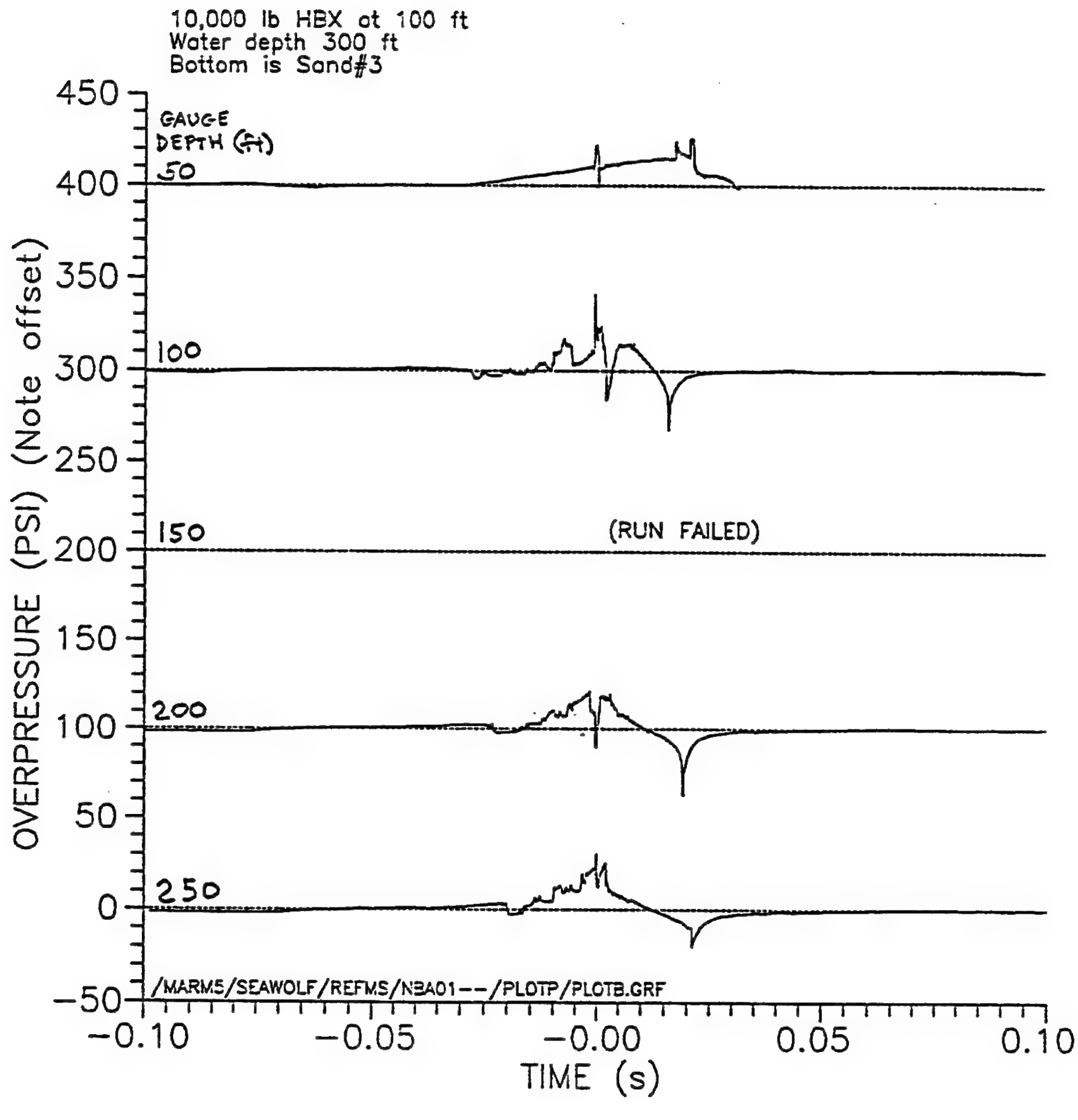


Fig. 10p— Norfolk–J P vs T, Shot 2, Range 1 NM, Depths vary

PRELIMINARY

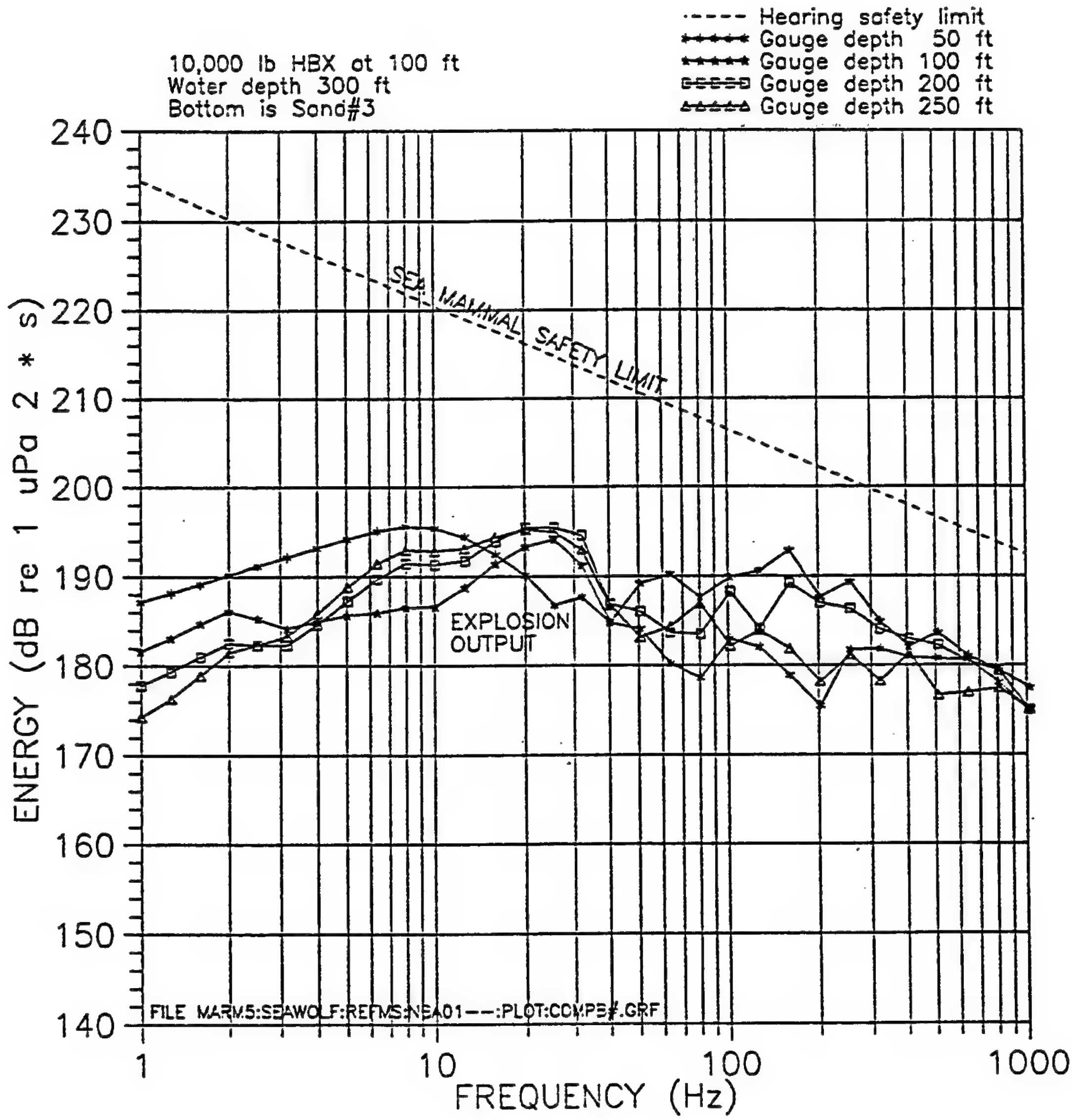


Fig. 10e— Norfolk–J E vs F, Shot 2, Range 1 NM, Depths vary

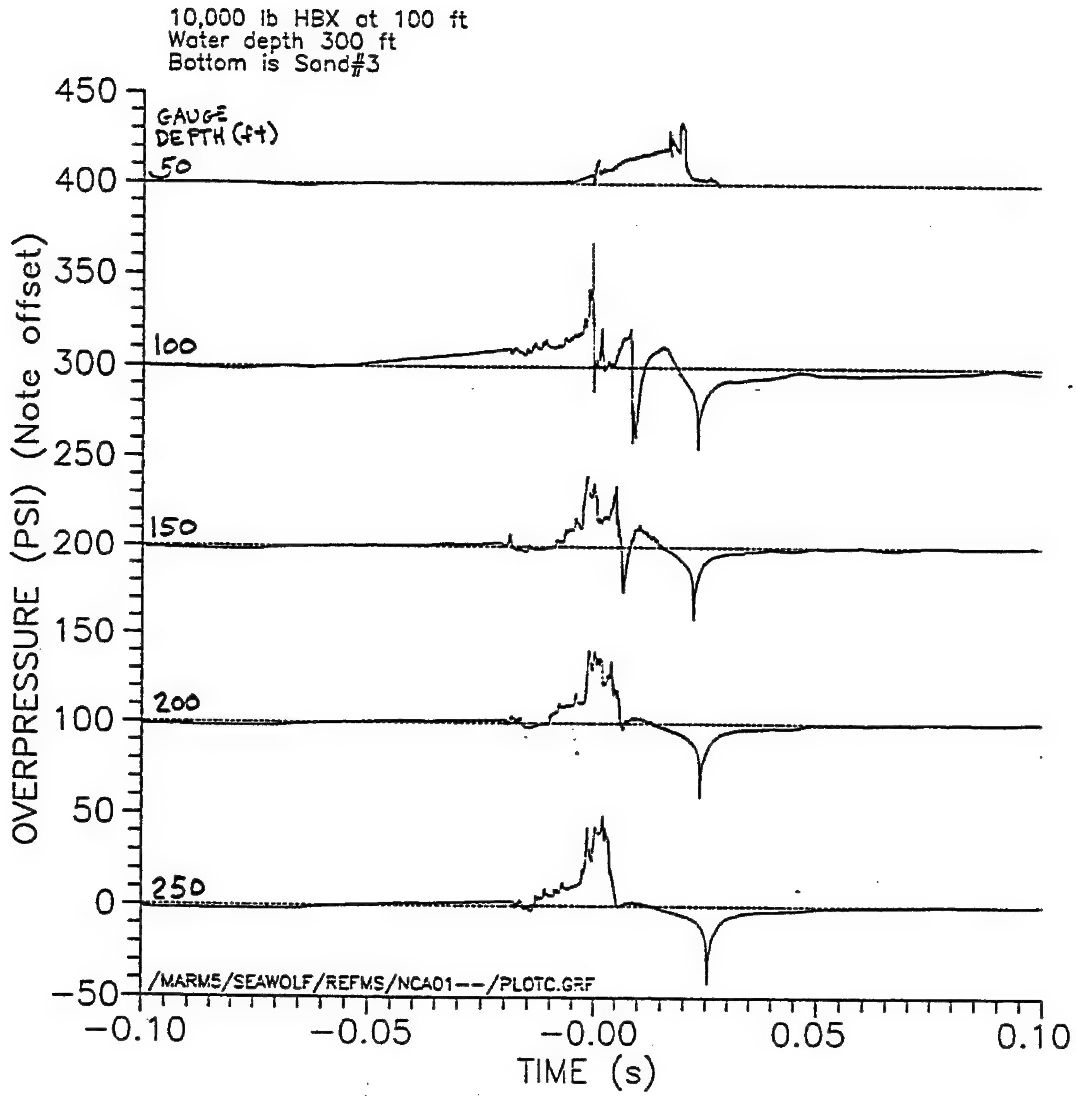


Fig. 11p – Norfolk–J P vs T, Shot 3, Range 1 NM, Depths vary

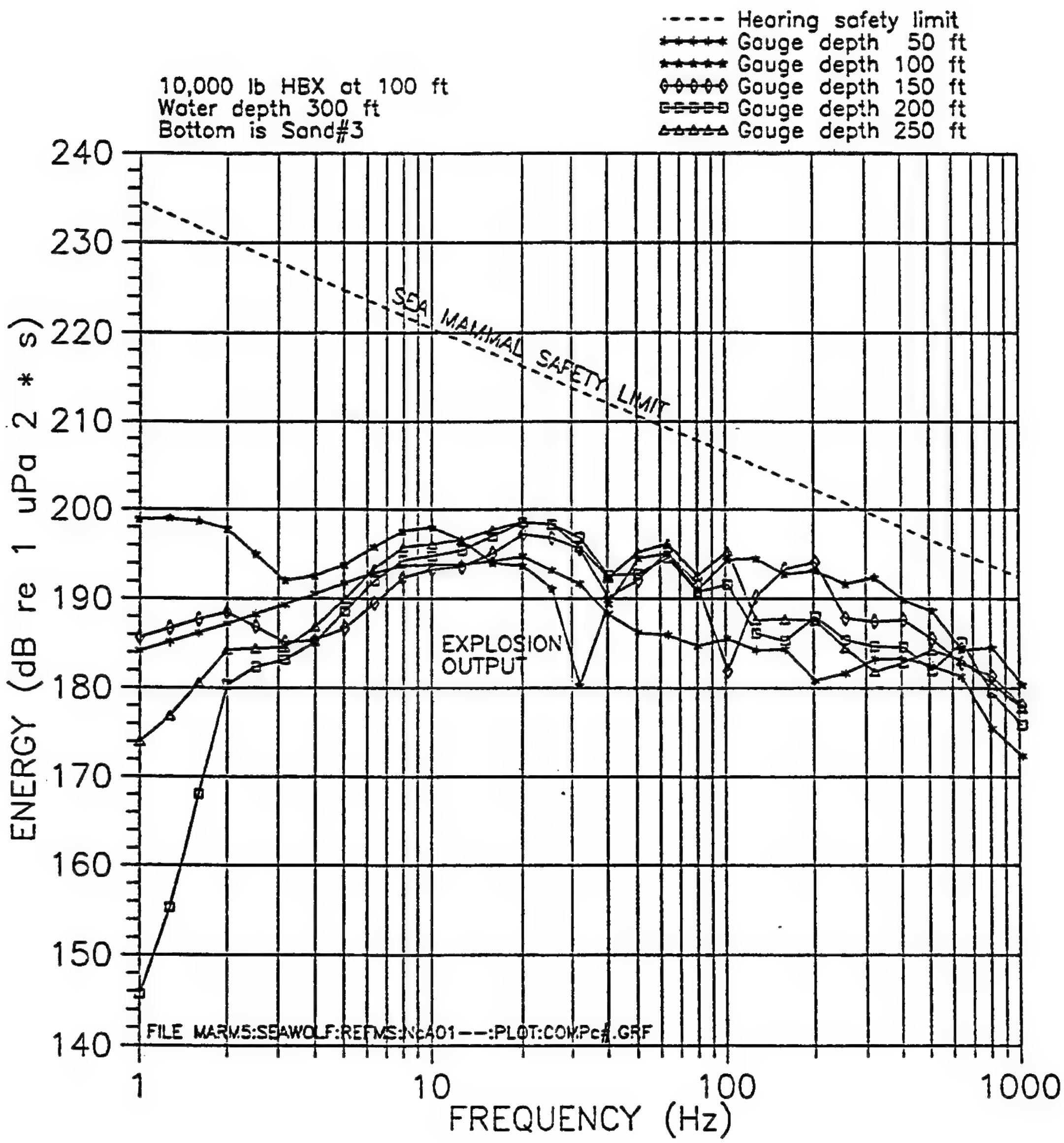


Fig. 11e– Norfolk–J E vs F, Shot 3, Range 1 NM, Depths vary

PRELIMINARY

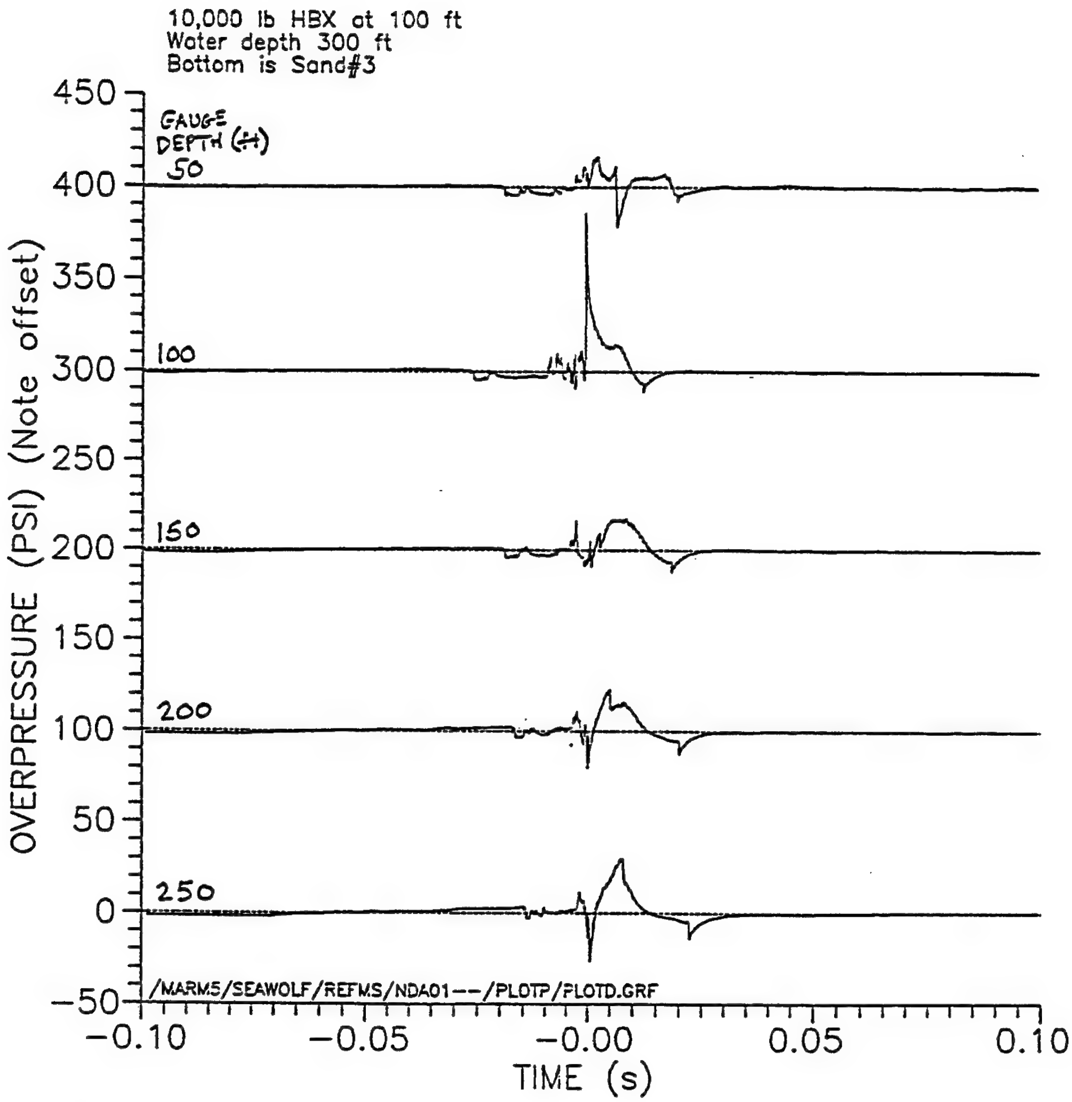


Fig. 12p— Norfolk-J P vs T, Shot 4, Range 1 NM, Depths vary

PRELIMINARY

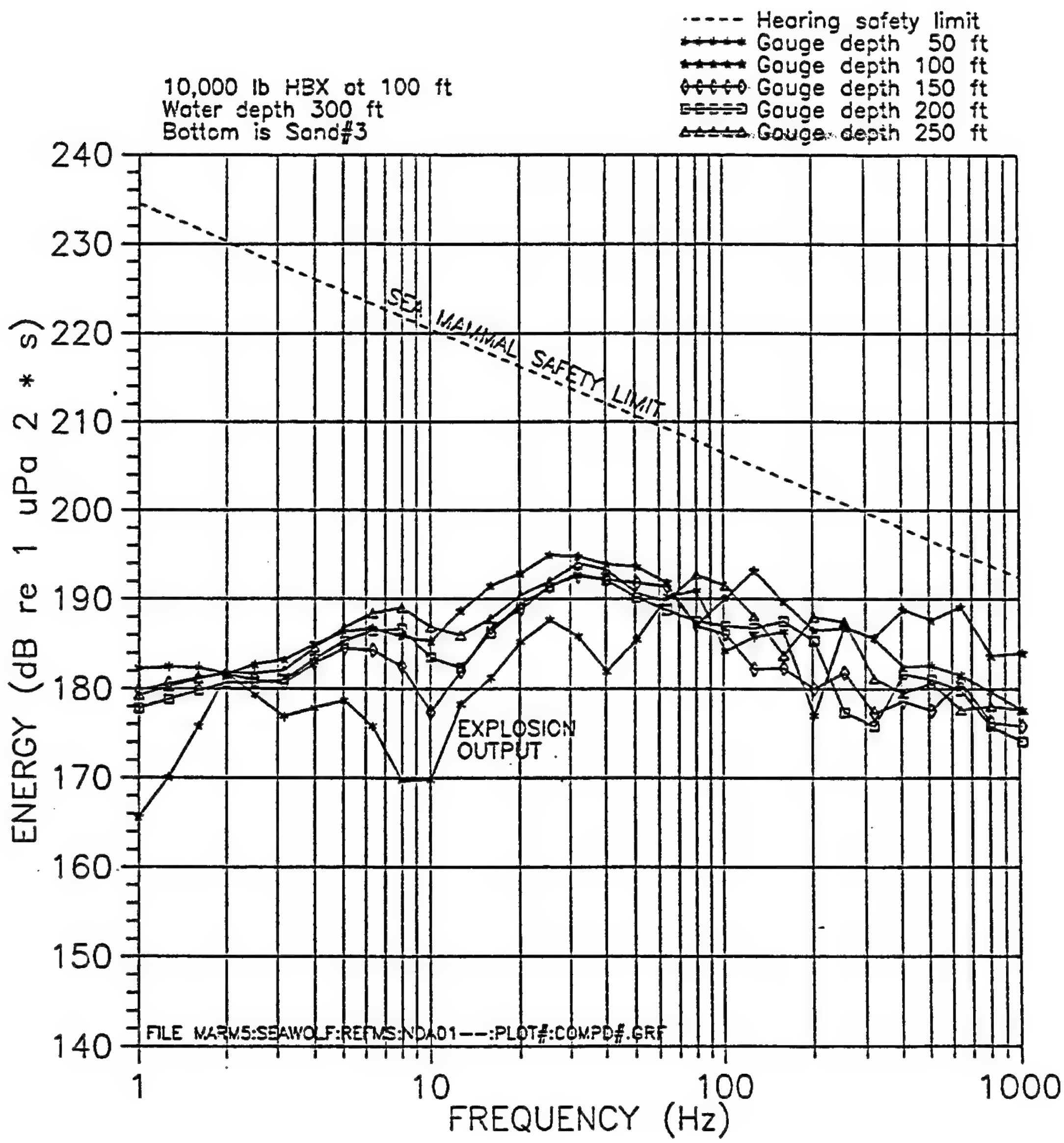


Fig. 12e— Norfolk–J E vs F, Shot 4, Range 1 nmi, Depths vary

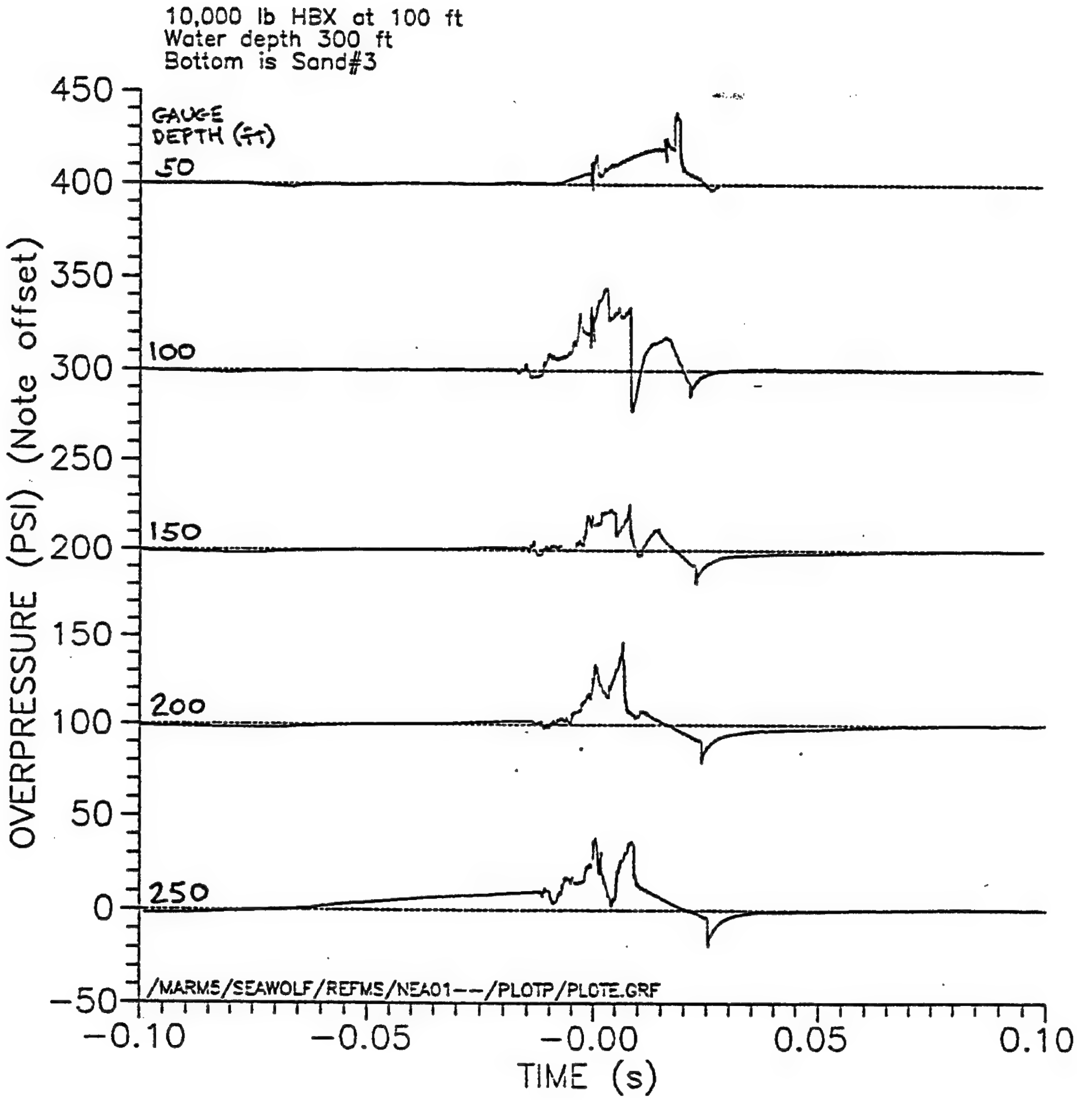


Fig. 13p – Norfolk–J P vs T, Shot 5, Range 1 NM, Depths vary

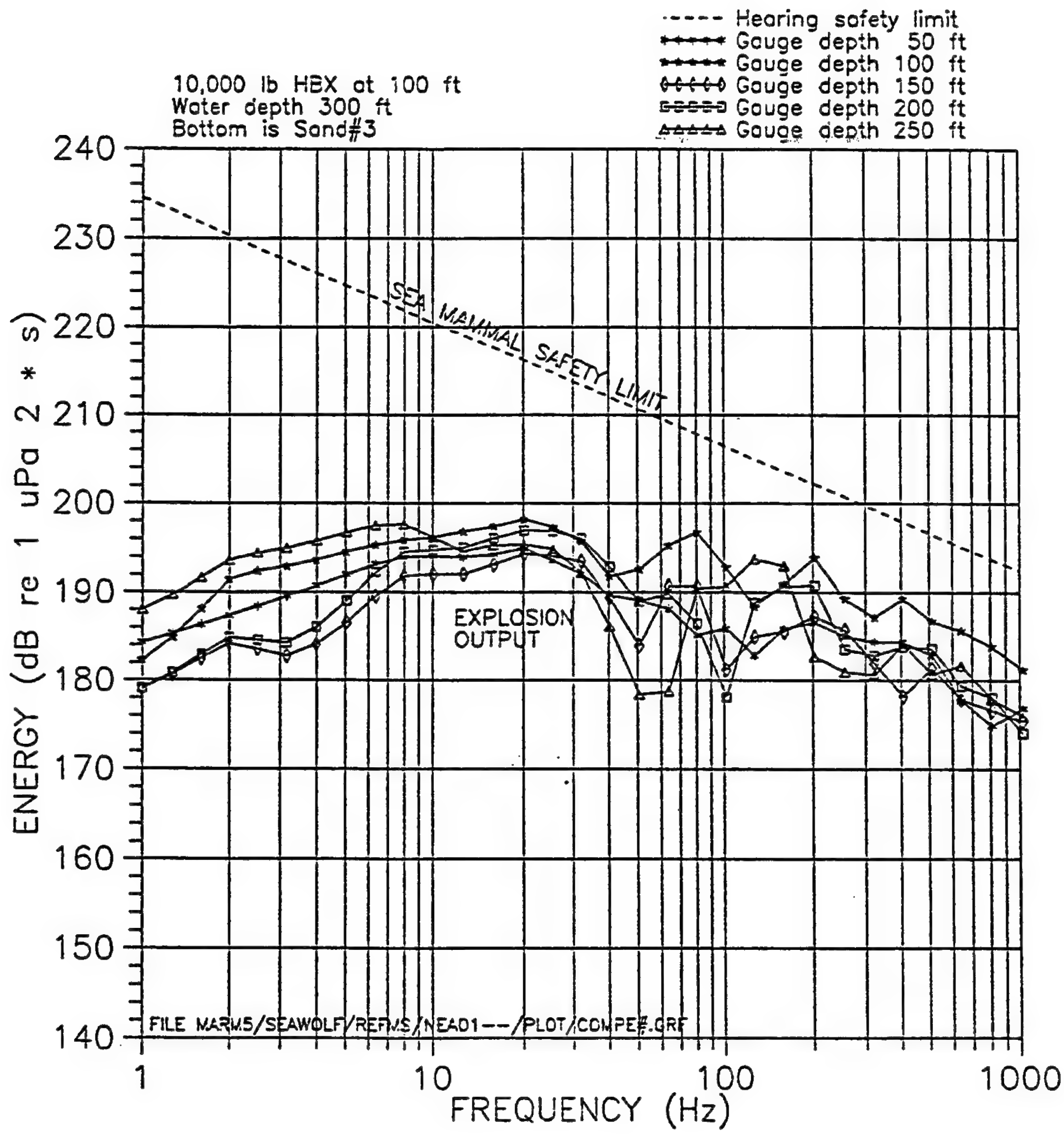


Fig. 13e— Norfolk–J E vs F, Shot 5, Range=1 NM, Depths vary

PRELIMINARY

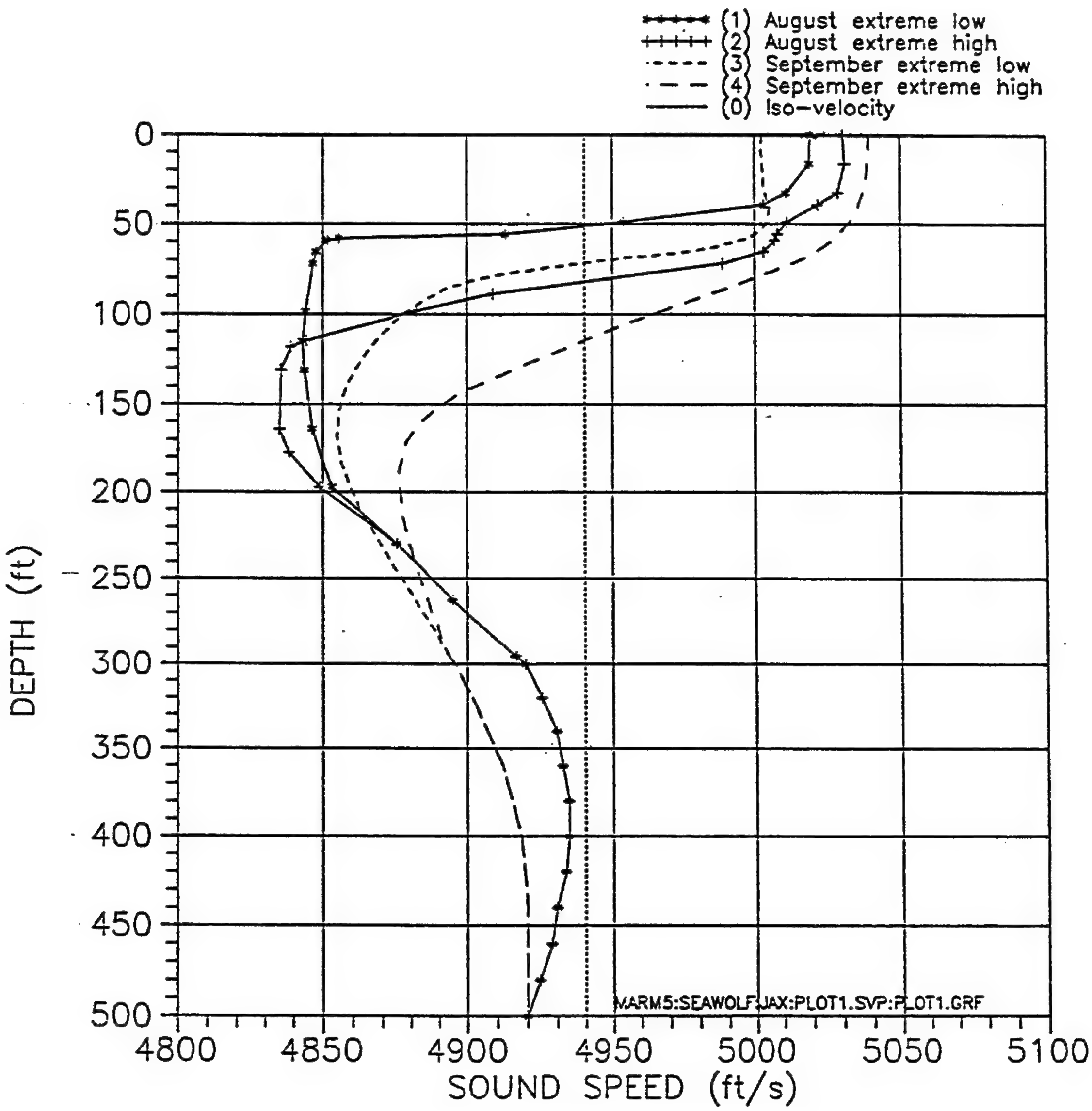


Fig. 14 – Norfolk–S Site SVPs

PRELIMINARY

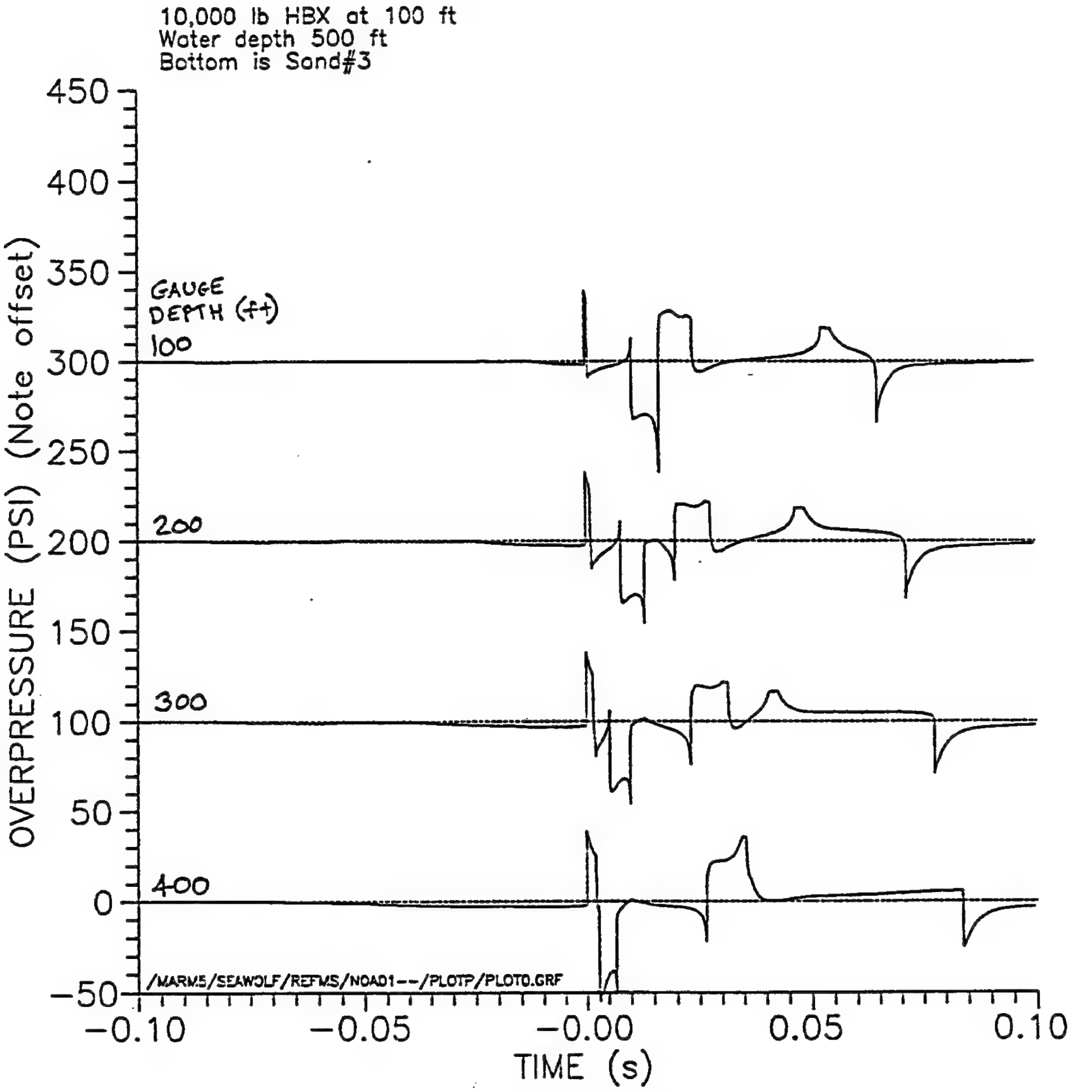


Fig. 15p — Norfolk–S P vs T, SVP 0, Range 1 NM, Depths vary

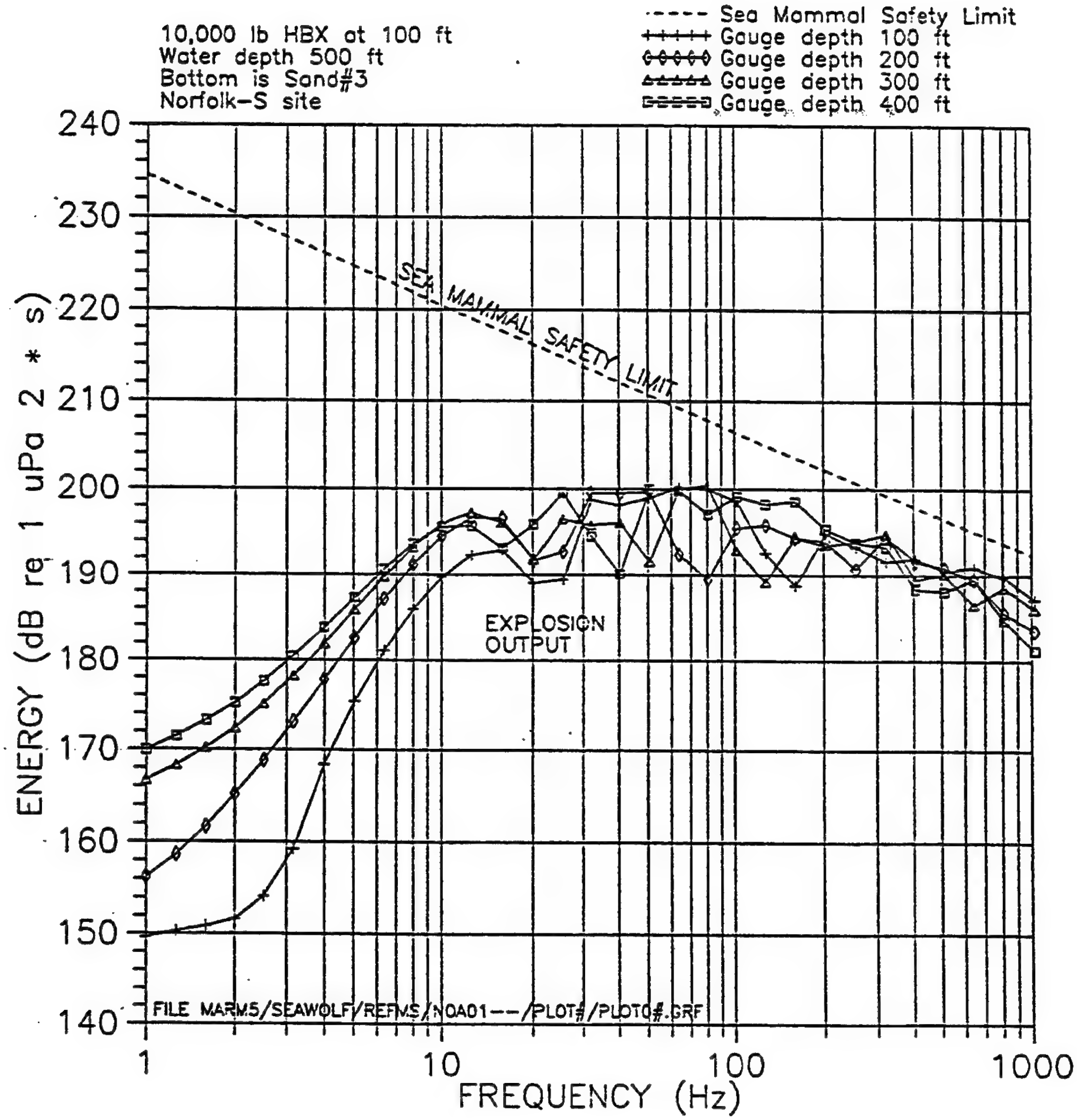


Fig. 15e– Norfolk–S E vs F, SVP 0, Range 1 NM, Depths vary

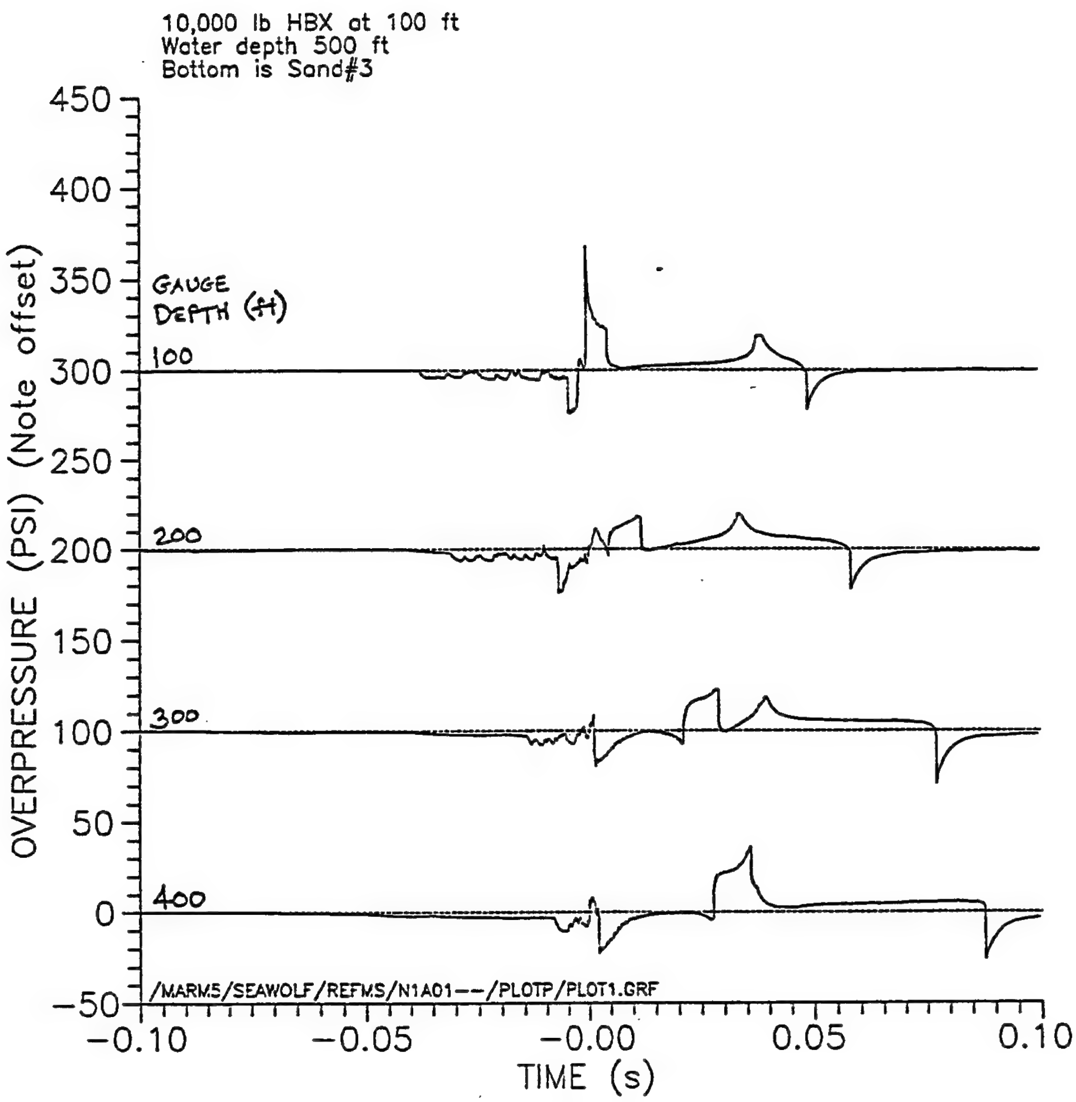


Fig. 16p− Norfolk−S P vs T, SVP 1, Range 1 NM, Depths vary

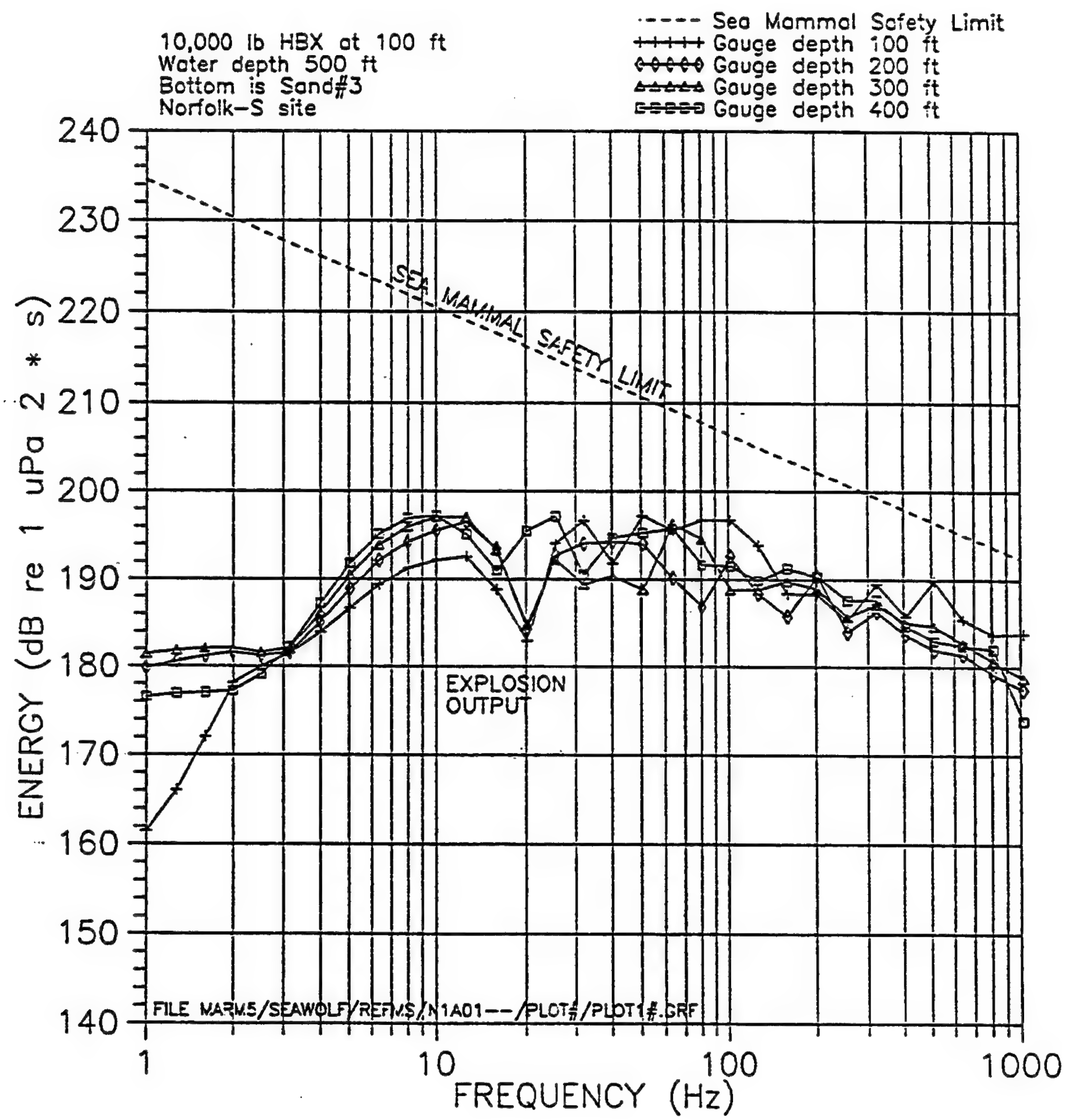


Fig. 16e — Norfolk–S E vs F, SVP 1, Range 1 NM, Depths vary

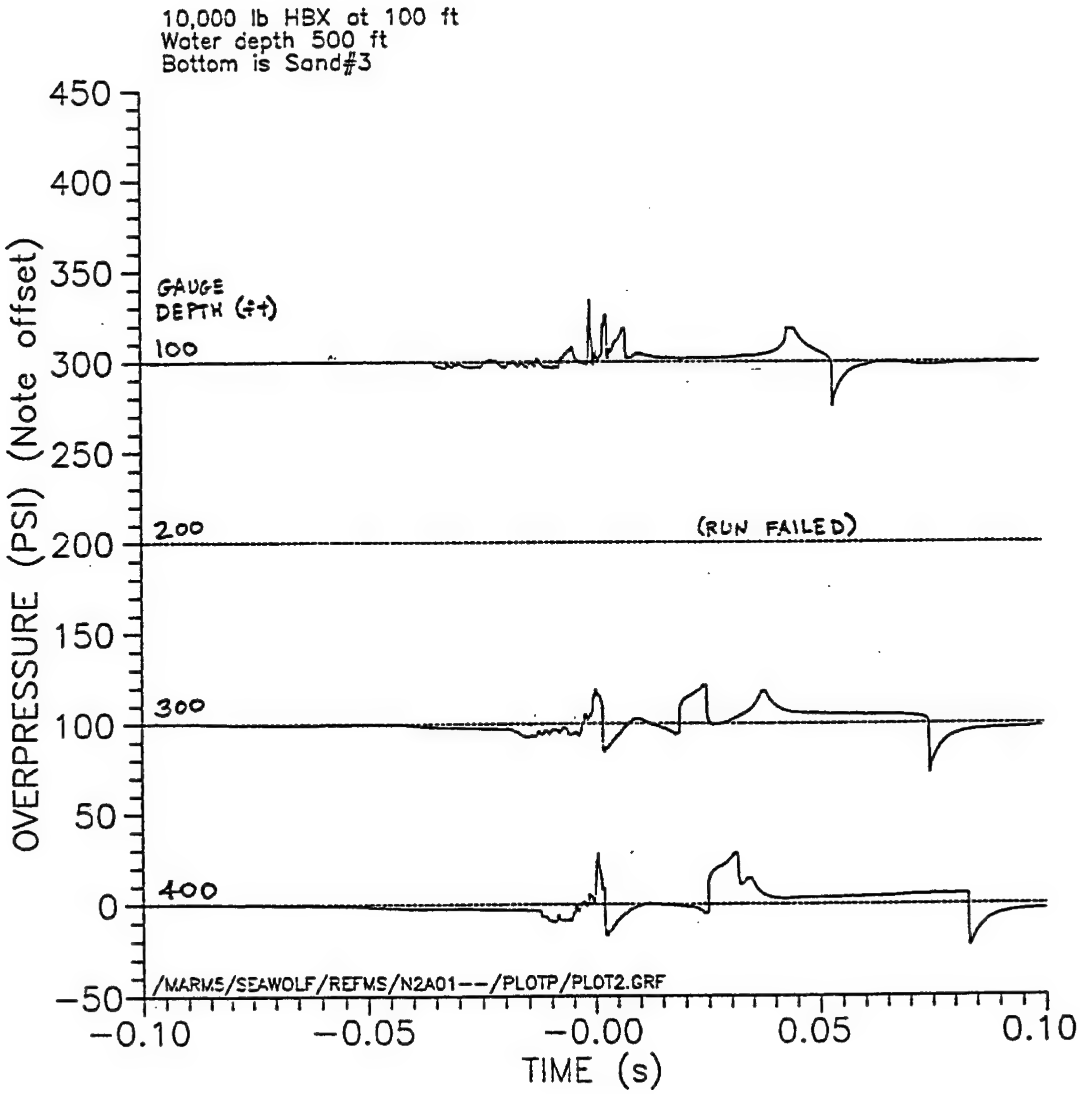


Fig. 17p – Norfolk–S P vs T, SVP 2, Range 1 NM, Depths vary

PRELIMINARY

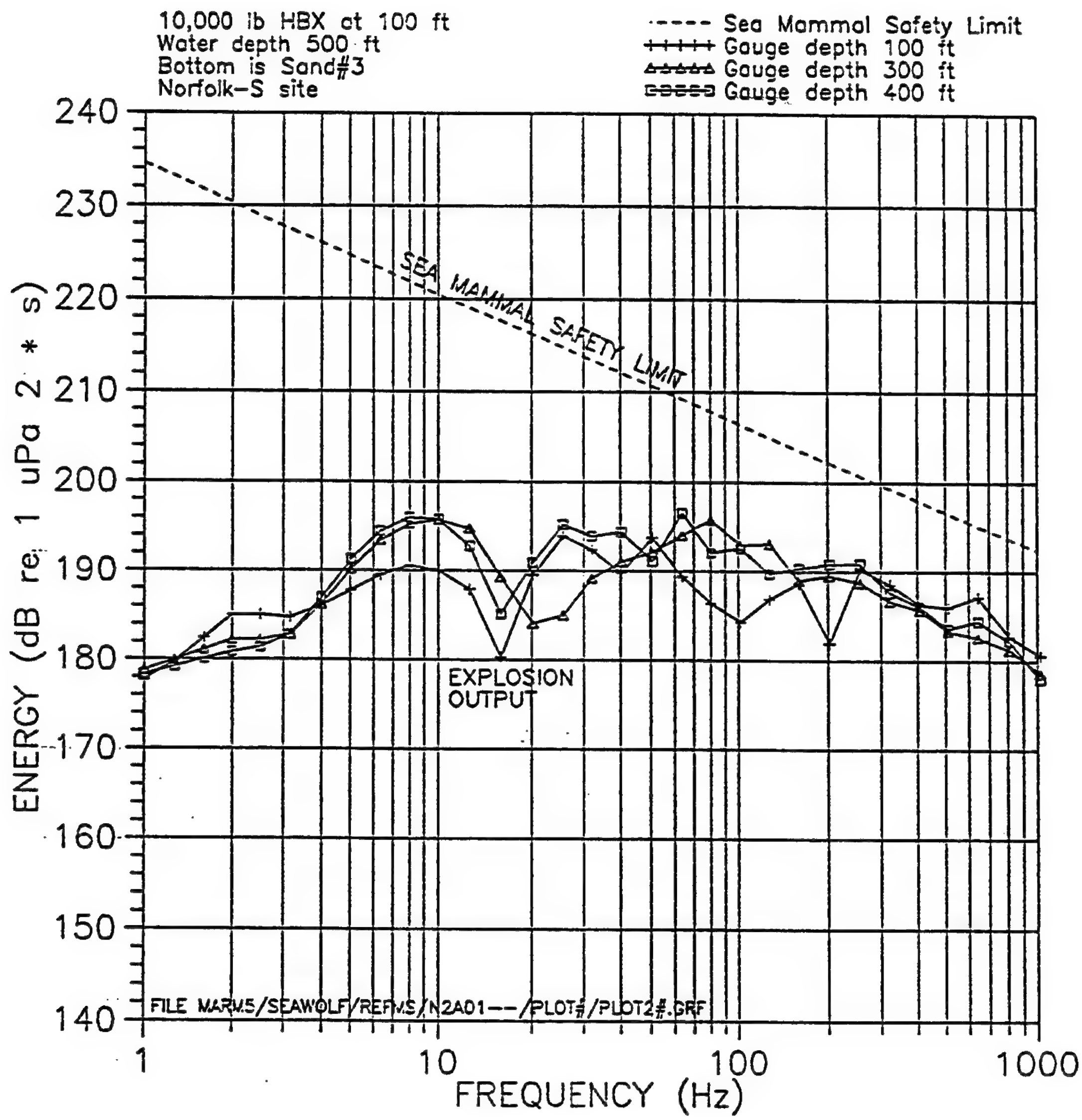


Fig. 17e – Norfolk–S E vs F, SVP 2, Range 1 NM, Depths vary

PRELIMINARY

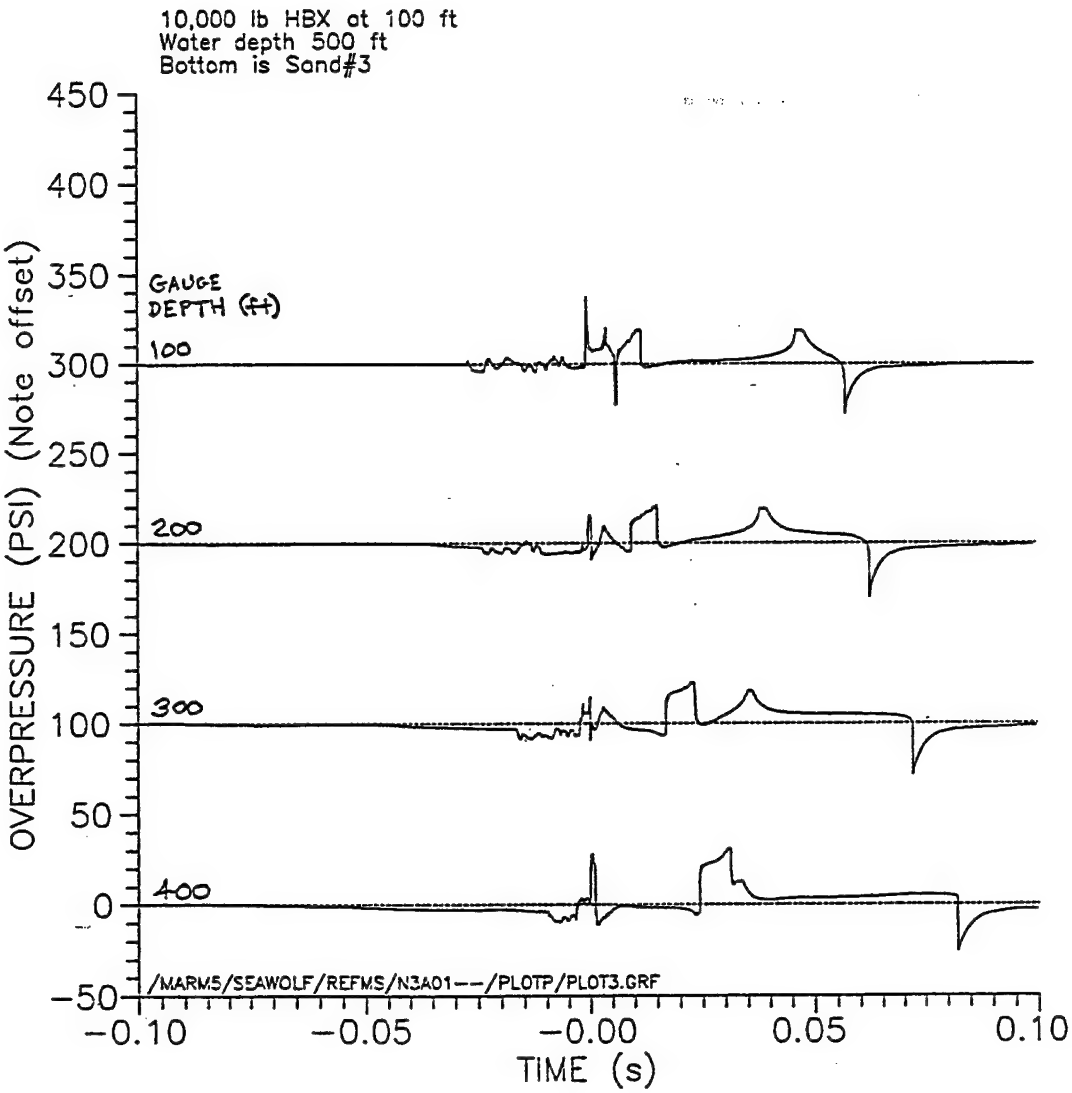


Fig. 18p – Norfolk–S P vs T, SVP 3, Range 1 NM, Depths vary

PRELIMINARY

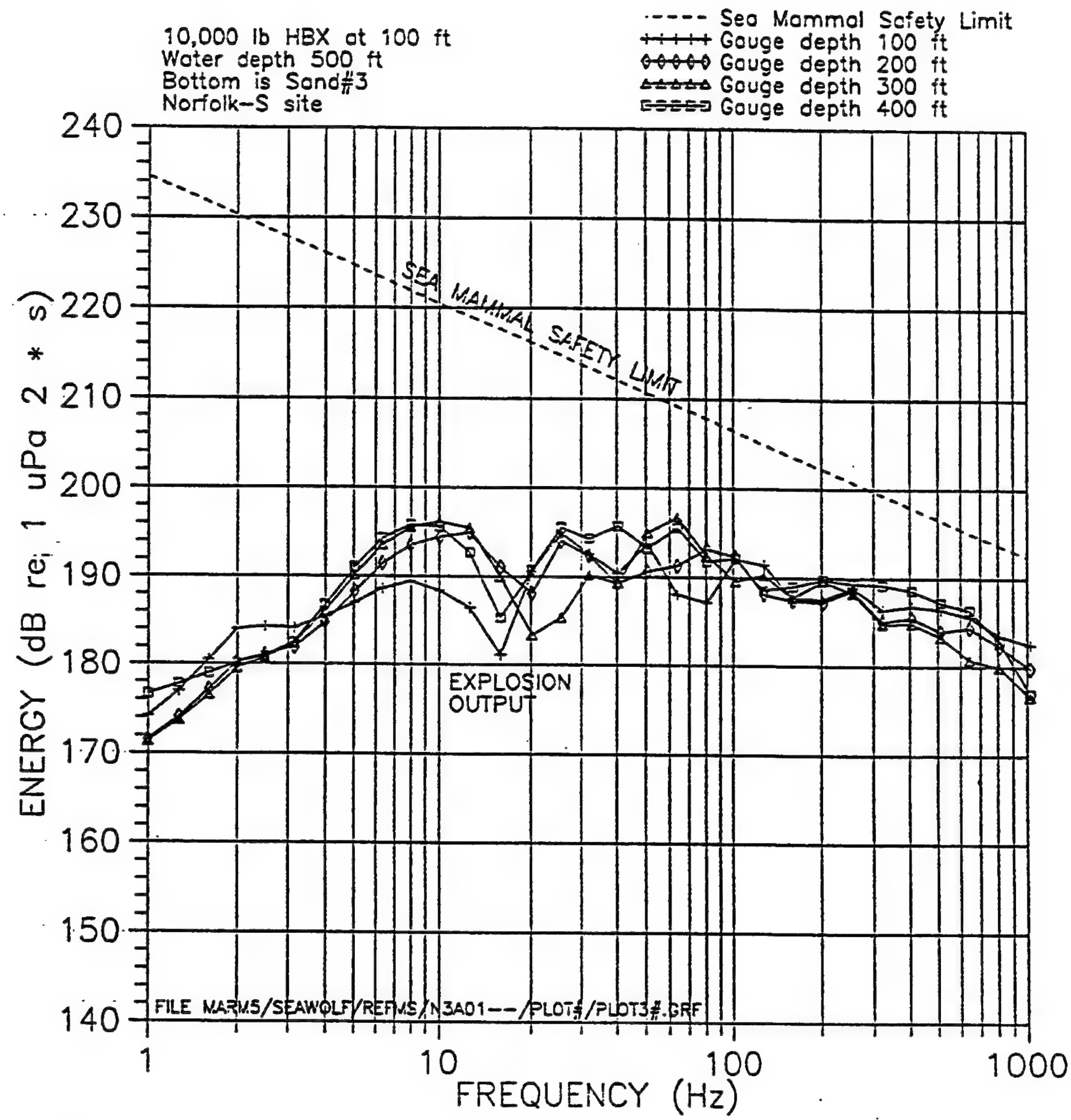


Fig. 18e— Norfolk–S E vs F, SVP 3, Range 1 NM, Depths vary

PRELIMINARY

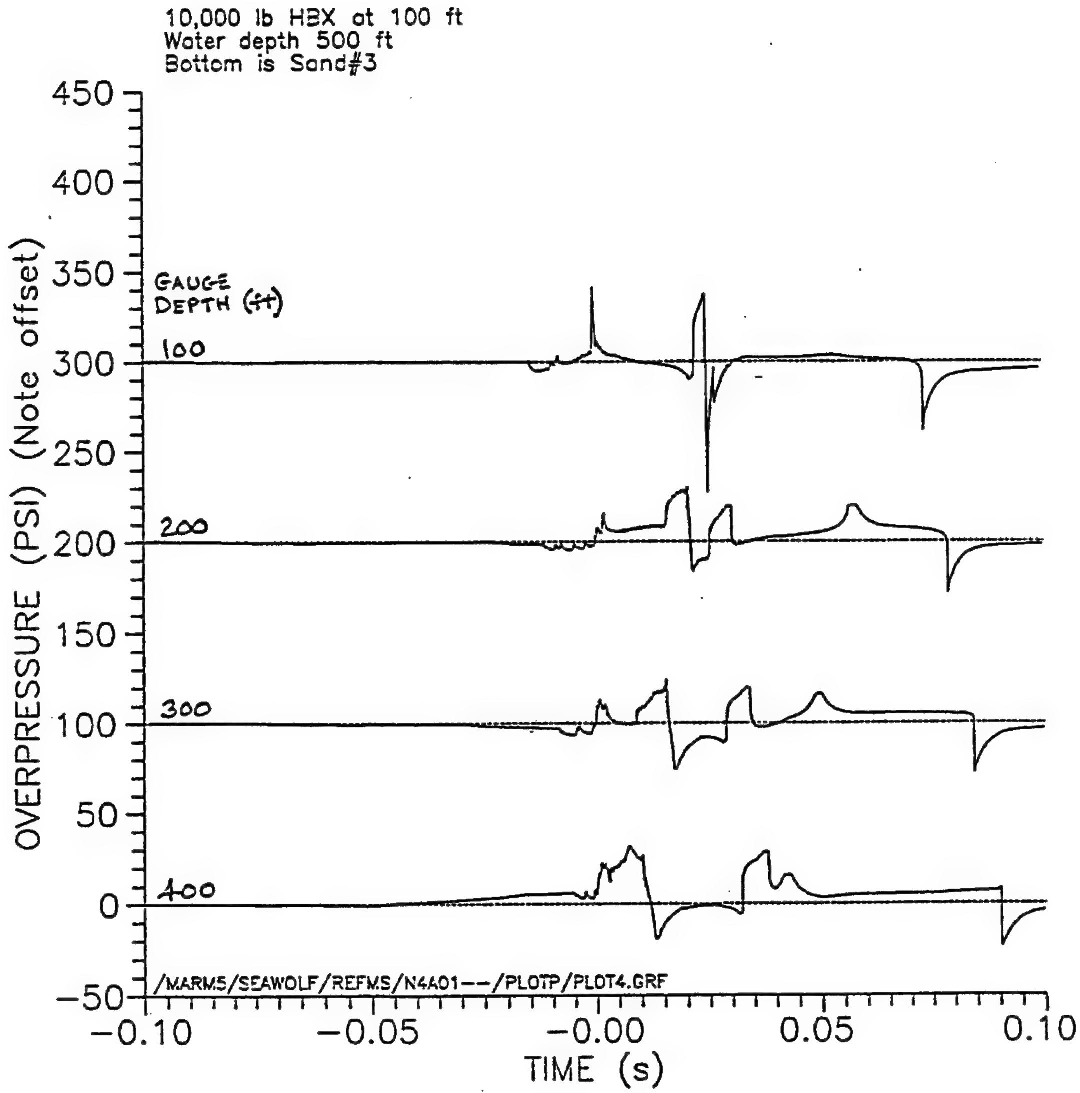


Fig. 19p − Norfolk−S P vs T, SVP 4, Range 1 NM, Depths vary

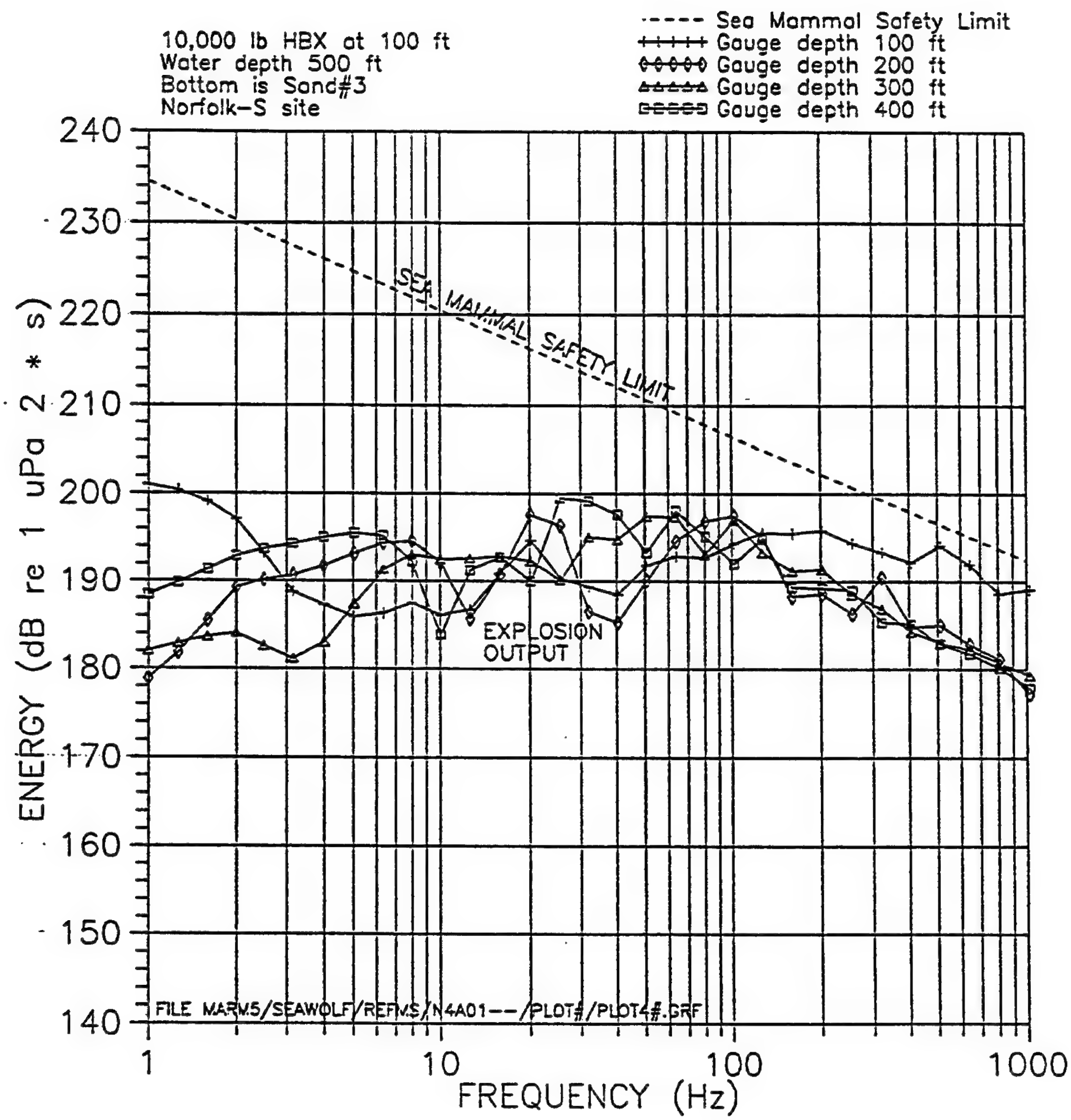


Fig. 19e — Norfolk–S E vs F, SVP 4, Range 1 NM, Depths vary

APPENDIX B

PROPOSED INTERIM SEA MAMMAL HEARING SAFETY CRITERION

Memorandum of 17 Dec 1995
by
D. L. Lehto

MEMORANDUM 17 Dec 1995

From: D. Lehto
To: J. A. Goertner

Subj: Proposed interim sea mammal hearing safety criterion

INTRODUCTION

This memo presents a safety criterion that is a slight tweaking of the figure entitled "Placement of suggested whale hearing safety limit" presented at the Carderock meeting on 10 Apr 1995.

There are good data on the hearing sensitivity of marine mammals (ref. (1)), but essentially no data on damage levels. There is urgent need for an interim damage criterion that can be used until damage level data become available.

This memo proposes an interim damage criterion based on human data. It is recognized that humans are not sea mammals, but we have to use the data we have.

HUMAN DATA

Human data from ref.(3b) are shown in Figure 1. ("Phons" are the dB levels at 1 kHz. Each curve is of a constant sensitivity to the sound.) The "0" curve is the minimum audible level. The "100" curve is regarded as a "not safe" level for brief, repeated exposures (ref. 3c, p. 470). Since we are interested in single brief (under 1 second) pulses, we use the "120" curve as the maximum allowed level. Note that in ref. (4), humans were exposed to more than 120 dB (below 50 Hz) for 2 to 3 minutes without physical damage.

The human data (from refs. 3 & 4) are used as follows:

(1) Shift the frequency up by a factor of 10. This was recommended by a reviewer as a way to match sea mammal hearing.

(2) Shift the dB levels to match at the most sensitive part of the hearing threshold curves.

The resulting data are shown on Figure 2. The solid curves are the shifted human data; the data points are sea mammal hearing threshold data from ref. (1).

The straight line that skims the bottom of the "human discomfort" curve is a proposed safety limit for sea mammal hearing, but it is for brief single pulses of pure tones. It needs to be converted to an energy criterion so it can be used for comparison with explosion pulses. The straight line is

$$dB = 215 - 15*Log(Hz).$$

ENERGY-BASED SAFETY LIMIT FOR PURE TONES

Changing to energy is easily done by integrating the single tone over the integration time (Ti) of the ear:

$$dB = 215 - 15*Log(Hz) + 10*Log(Ti)$$

The integration time of the human ear is 0.1 to 0.2 seconds. (The figure on p. 187 of Ref. (1), suggests Ti=1 second for the bottlenose dolphin, but this depends on what the long-signal level is; looking at the original curves given by Fay gives more like 0.2 seconds.) Note that the lower the integration time, the lower in dB the safety limit lies.

For Ti=0.2, 10*Log(Ti) is 7 and the safety limit becomes

$$\boxed{dB = 208 - 15*Log(Hz)}.$$

This line may be placed onto explosion output energy (dB re 1 uPa^2*s) vs frequency curves. Selected points are:

Hz	dB
1	208
10	193
100	178
1000	163
10000	148
100000	133

APPLYING THE SAFETY LIMIT TO EXPLOSIONS

Figure 3 shows an example of use of this safety limit. The explosion output data for three ranges are from Fig. 23 of Ref. (8). Four nautical miles is not quite acceptable as a safety range for this particular combination of sea bottom, charge size, water depth, charge depth, and sound velocity profile.

APPLICABILITY

This safety limit uses data for white whales, killer whales, and harbor porpoises. It also applies to the bottlenose dolphin, false killer whale, and boutu, which have audiograms similar to those in the preceding group (ref. (1), p. 185). It is not necessarily applicable to the large whales, which may have their maximum sensitivity at very low frequencies.

REFERENCES

Marine mammal hearing threshold data in water:

(1) W. J. Richardson, et al, "Effects of Noise on Marine Mammals," LGL Ecological Research Associates, Inc., Bryan, TX, done for Mineral Management Service, Herndon, VA, PB91-168914, Feb 91 [Underwater audiograms of odontocetes are on p. 180.]

Integration time of the ear:

(2) C. S. Johnson, "Relation between Absolute Threshold and Duration-of-tone Pulses in the Bottlenosed Porpoise," J. Acoust. Soc. Am. 43 (4) 757-763 (1968)

Human hearing data in air:

(3a) D. W. Robinson & R. S. Dadson, "Threshold of hearing and equal-loudness relations for pure tones, and the loudness function," J. Acoust. Soc. Am. 29(12):1284-1288 (1957). [Not on hand.]

(3b) F. A. Everest, The Master Handbook of Acoustics, 3rd ed. (Tab Books, McGraw-Hill, N. Y., 1994) [p. 43; quotes ref. (3a). Integration time is on p. 48.]

(3c) E. J. McCormick, Human Factors Engineering (McGraw-Hill, N.Y., 1964). [p. 69; quotes ref. (3a).]

(4) P. M. Edge, Jr. & W. H. Mayes, "Description of Langley Low-Frequency Noise Facility and Study of Human Response to Noise Frequencies Below 50 cps," NASA TN D-3204, 1966. [I'm not sure what they mean by dB level of their 1/3 octave white noise.]

Human data in water:

(5) W. E. Montague & J. F. Strickland, "Sensitivity of the Water-Immersed Ear to High- and Low-Level Tones," J. Acoust. Soc. Am. 33(10):1376-1381 (1961). [Humans underwater can tolerate 200 dB of 1500 Hz pure tone; plotting this on Figure 4 shows that the sea mammal safety line is very conservative for humans.]

Explosion output data:

(6) Contractor Report DLL-1995-4, "The acoustic field at 4 NM range for a 10,000 lb shock test explosion 100 ft deep in 500 ft depth water," 24 Apr 1995. [This is still basically valid. Some differences have been noted in more recent work with all the REFMS refraction options turned on. This report is useful because it identifies each pulse. These "Contractor Reports" are available from NSWC/IH Code 460.]

(7) Contractor Report DLL-1995-6, "Proposed hearing-safe range for sea mammals in the vicinity of a large underwater explosion," 5 Jun 1995. [This report is still useful for its acoustic field calculations. The "Sea mammal safety limit" on the figures was shot down by expert review and should be replaced by the one presented in the present memo, which has not been shot down because it has not been reviewed yet.]

(8) Contractor Report DLL-1995-7, "Preliminary results on the acoustic field at 1, 4, and 16 NM from a large underwater explosion," 31 Jul 1995. [Uses historic seasonal sound velocity profiles for the SEAWOLF test area.]

(9) R. Thrun, NSWC/IH Code 460. [Many acoustic field calculations have been done with various sound velocity profiles.]

from F. A. Everest, The Master Handbook of Acoustics (TAB, 1994) 3rd ed., p. 41

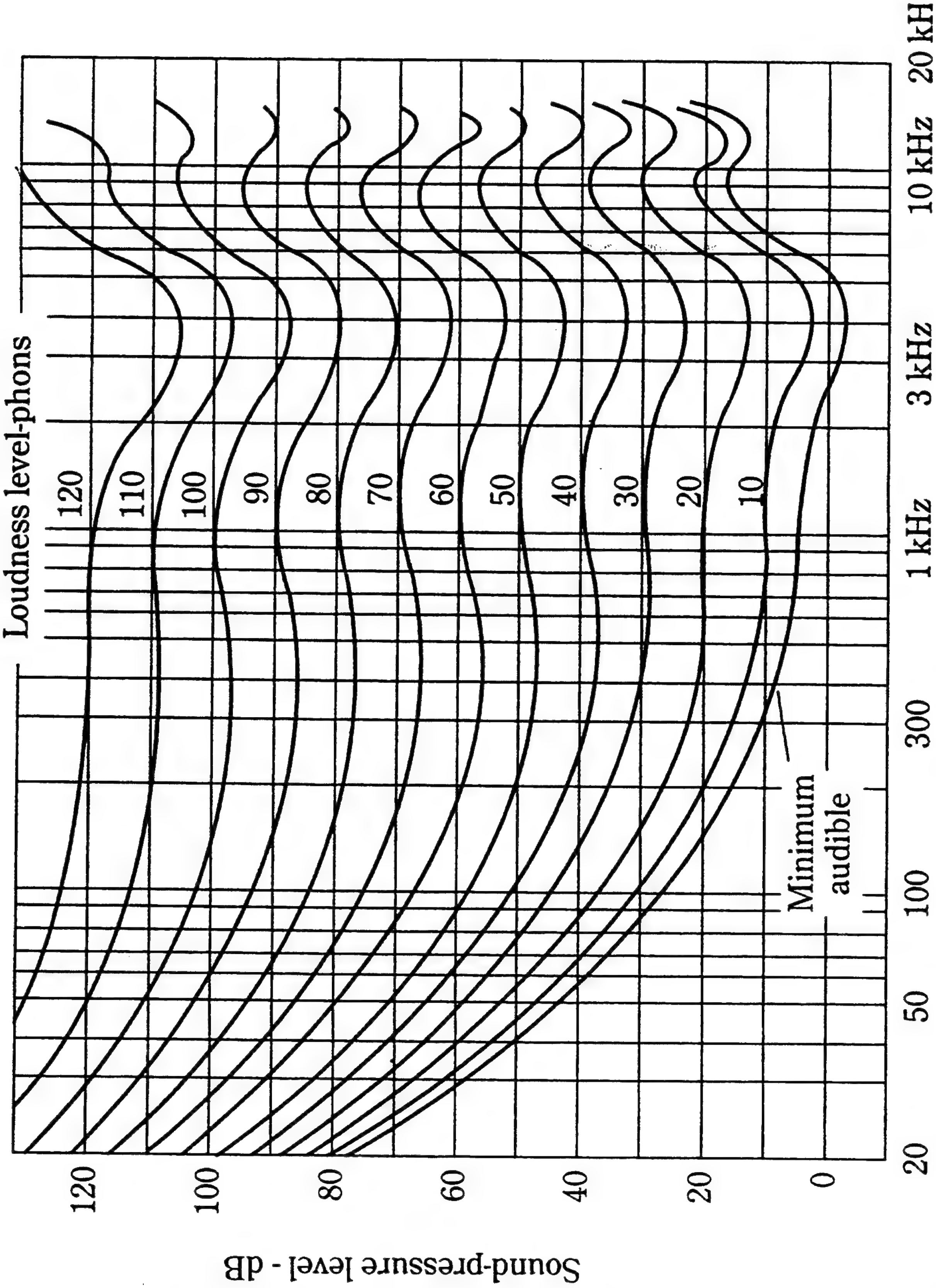


Fig. 1.- Equal-loudness contours of the human ear

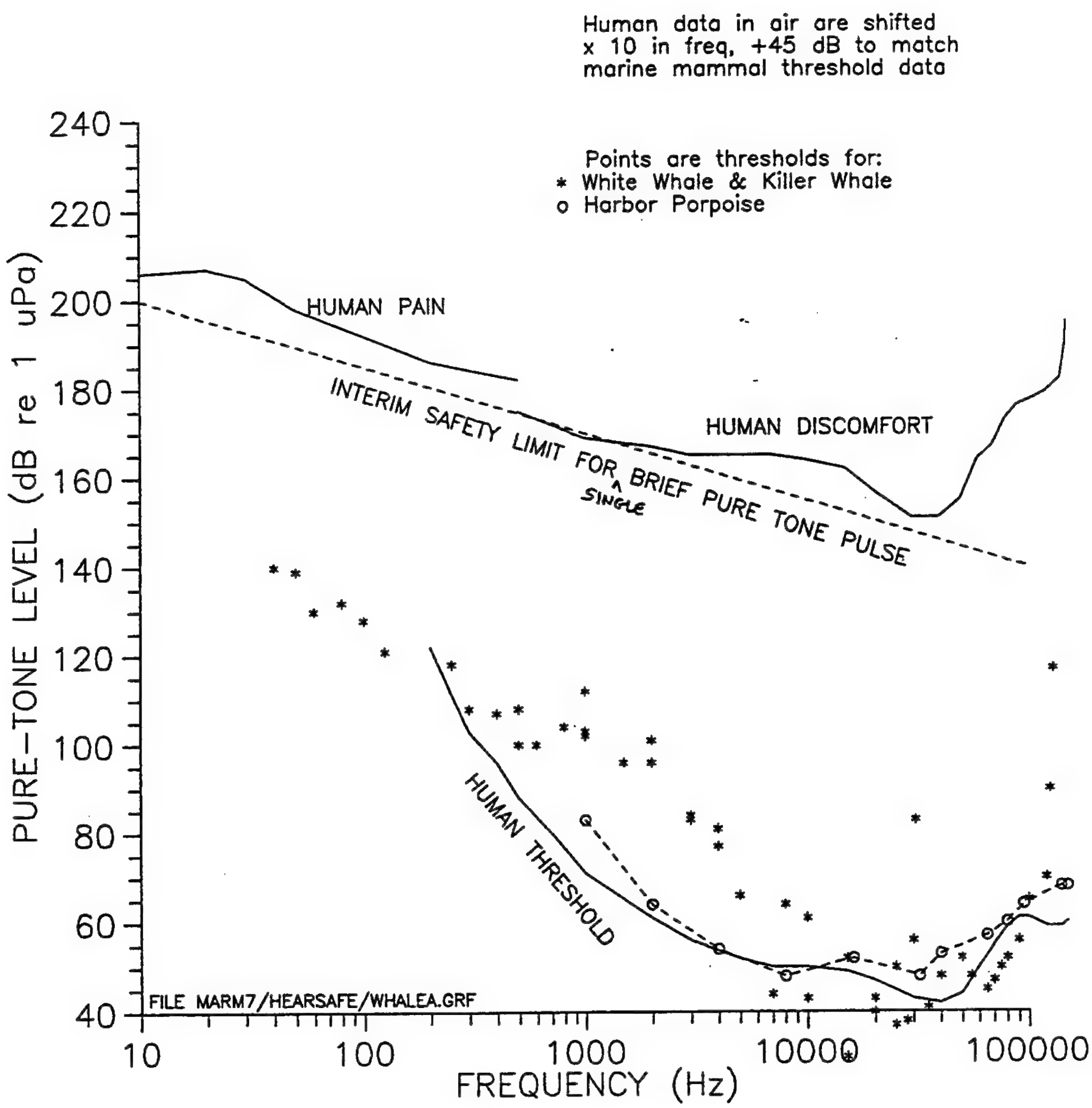


Fig. 2 — Interim Marine Mammal Hearing Safety Limit for Brief Pure Tones Based on Shifted Human Data in Air

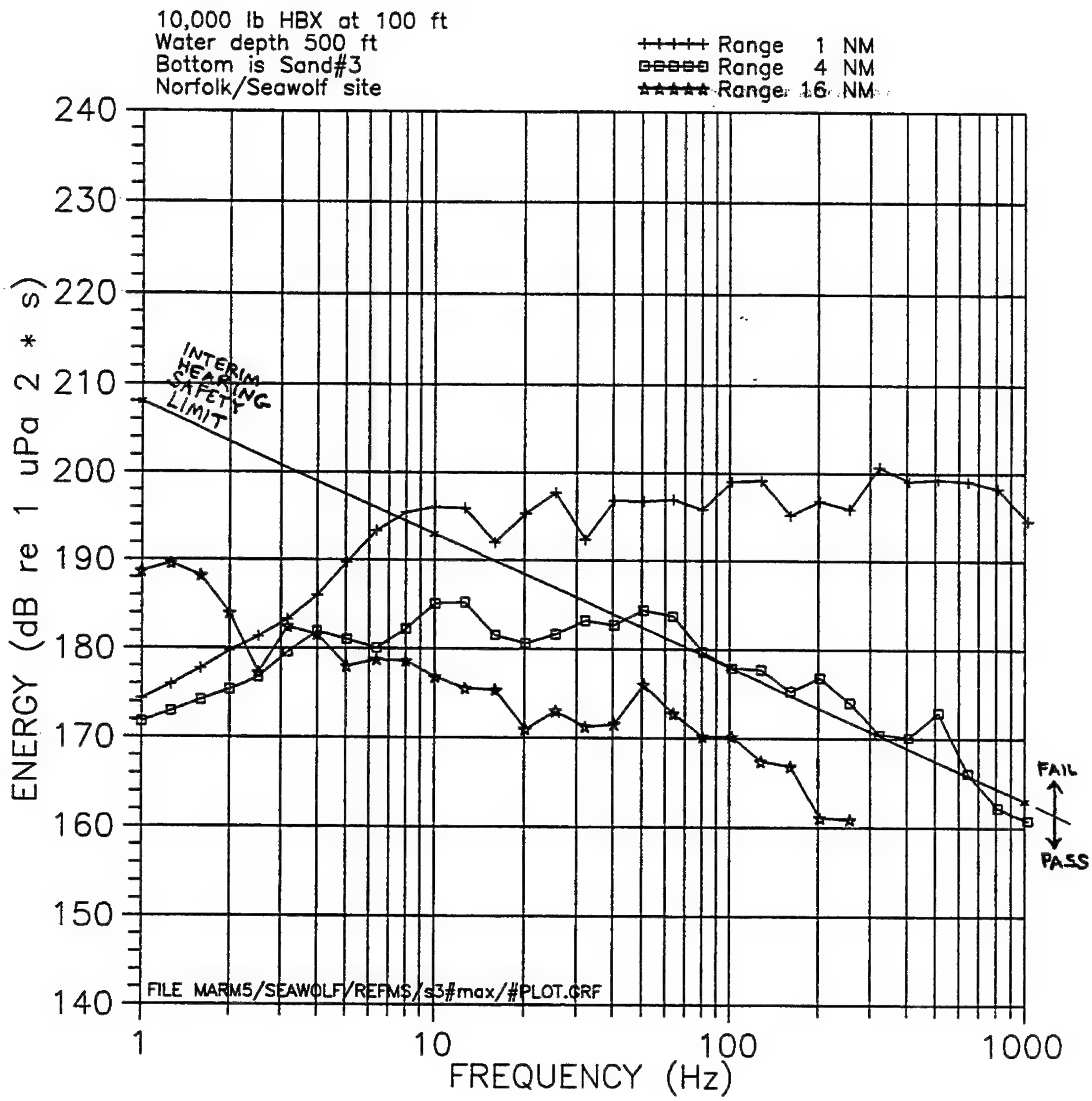


Fig. 3 — Example of Application of Hearing Safety Limit

APPENDIX C

WHY THE 120 DB HEARING CURVE WAS CHOSEN

Memorandum of 17 Jan 1995
by
D. L. Lehto

17 Jan 1996

MEMORANDUM

From: D. Lehto
To: J. A. Goertner

Subj: Why the 120 dB hearing curve was chosen

Ref: (1) Memo D. Lehto to J. A. Goertner, "Proposed interim sea mammal hearing safety criterion, 17 Dec 1995.

(2) W. D. Ward, "Damage-Risk Critera for Line Spectra," J. Acoust. Soc. Am. 34(10:1610-1619 (1962). [Humans in air.]

INTRODUCTION

Ref. (1) used the human-in-air hearing curve of 120 dB (re 20 µPa) as the basis for estimating a no-damage criterion for several species of sea mammals.

The data of Ref. (2) are used here to justify the choice of the 120 dB curve.

A 120 dB TONE GIVES 30 dB TTS

Fig. 2 of Ref. (2) shows that a 1 minute exposure of humans to a 120 dB SPL (re 20 µPa) 1700 Hz pure tone results in a temporary threshold shift (TTS) of 26 dB at 3 kHz (measured 20 seconds after exposure).

Fig. 3 of Ref. (2) suggests that the highest TTS for a 1700 Hz tone is at 2 KHz and is 3 dB higher than at 3 KHz.

[A 700 Hz tone gives a similar TTS to the 1700 Hz tone (Figs. 9 and 10 of Ref. (2); these data are at 5 minutes after a 5 minute exposure, so the comparison is not exact.]

Using 30 dB TTS for 120 dB is conservative for our application because:
[1] Ref. (2) used 125 dB without damage;
[2] The duration of interest is 0.2 seconds rather than 1 minute;
[3] The data in Fig. 2 of Ref. (2) for 120 dB are immediately preceded by tests at 105, 110, and 115 dB at two minute intervals, so the effective exposure time was greater than 1 minute.

30 dB TTS IS "NO DAMAGE"

Fig. 9 of Ref. (2) shows that recovery (at 1 kHz) from ~30 dB TTS reaches 10 dB TTS in about 10 minutes; full recovery follows (no permanent threshold shift, i.e., no damage).

APPENDIX D

APPLYING THE DATA OF REF. (1)

Memorandum of 28 Jan 1996
by
D. L. Lehto

28 Jan 1996

MEMORANDUM

From: D. Lehto
To: J. A. Goertner

Subj: Applying the data of Ref. (1)

References:
(1) P.F.Smith, et al, "Underwater hearing in Man: II. A comparison of temporary threshold shifts induced by 3500 Hertz tones in air and underwater," Submarine Medical Research Laboratory, U. S. Naval Submarine Medical Center Report No. 608, Submarine Base, Groton, Conn., 15 Jan 1970. [Note that the db levels are re 20 uPa; current practice for underwater sound is to use db re 1 uP, a difference of 26 db.]

(2) Memo D. Lehto to J. A. Goertner, "Proposed interim sea mammal hearing safety criterion, 17 Dec 1995.

(3) F. A. Everest, The Master Handbook of Acoustics, 3rd ed. (Tab Books, McGraw-Hill, N. Y., 1994) [p. 41]

Encl: (a) Fig. 3 of Ref. (1) [human TTS in air and water]
(b) Fig. 1 of Ref. (3).[loudness vs frequency]
(c) Fig. 3 of Ref. (2).[pure-tone human & sea mammal data]
(d) Fig. 4 of Ref. (2).[energy safety criterion]

DISCUSSION

Recently discovered Ref. (1) has TTS data for humans in air and in water for 3500 Hz tones of 15 minute duration. Encl. (a) shows their main results.

We are interested in the meaning of the 120 db perceived loudness curve (in air) shown on Encl. (b). The Ref. (1) in-air data gives a 17 db TTS at 3500 Hz on the 120 db curve. This data point is significant to us; it reinforces the use of the 120 db curve as a no-damage level.

In water, Encl. (a) shows a 30 db TTS (slightly extrapolated) for exposure to 206 db re 1 uPa. This is plotted on Encl. (c) as pressure and on Encl. (d) as energy (with 0.2 second integration time). These new data points are of minor significance to us; we have been warned not to directly compare humans with sea mammals. These data merely show that the proposed sea mammal safety criterion is very conservative for humans and makes the criterion slightly more credible.

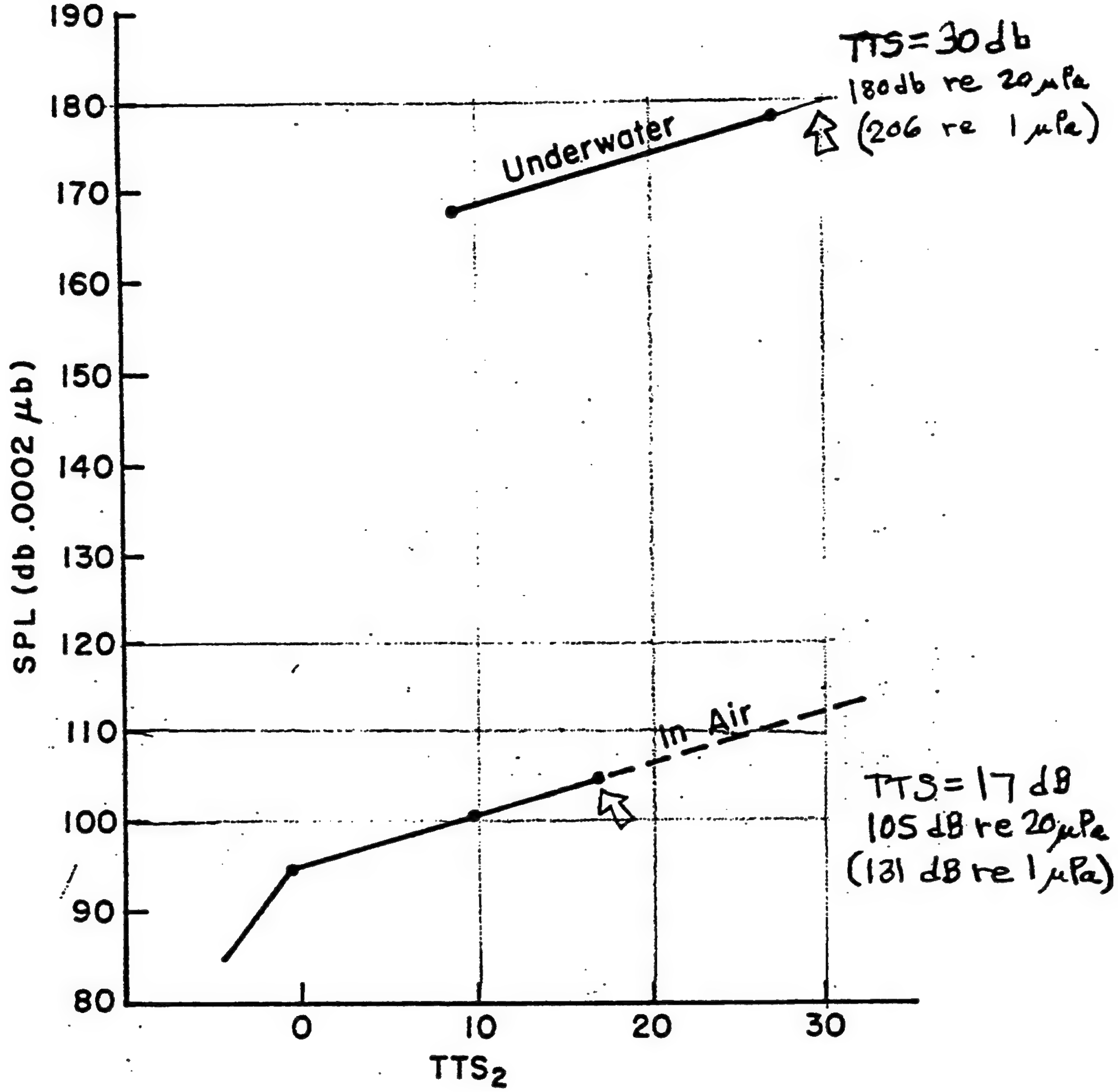


Fig. 3 of Ref (1). Median temporary threshold shift existing two minutes after exposure to 3500 Hertz tones in air and underwater.

ENCL. (a)

from F. A. EVEREST, The Master Handbook of Acoustics (TAB, 1994) 3rd ed., p. 41

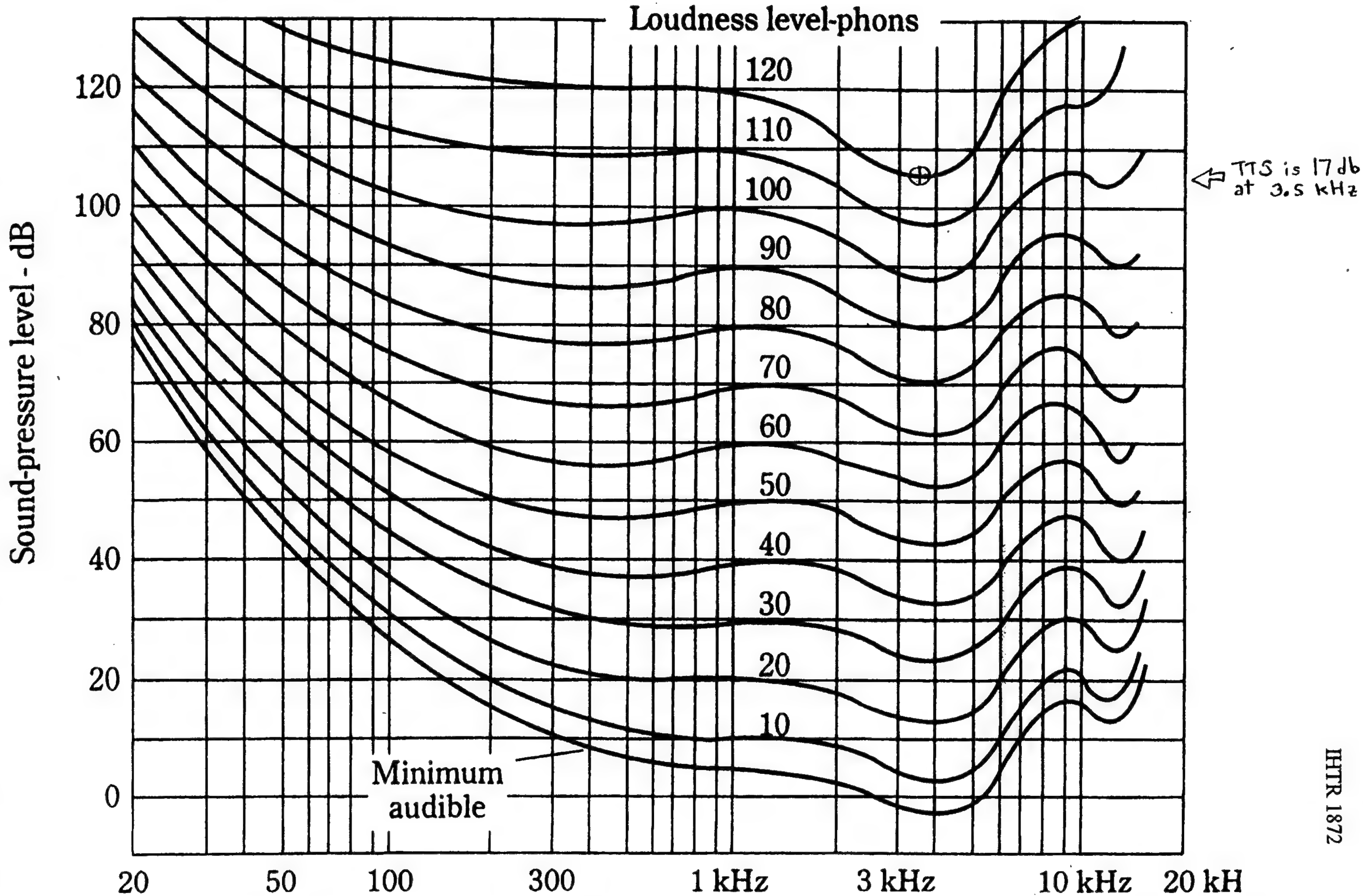
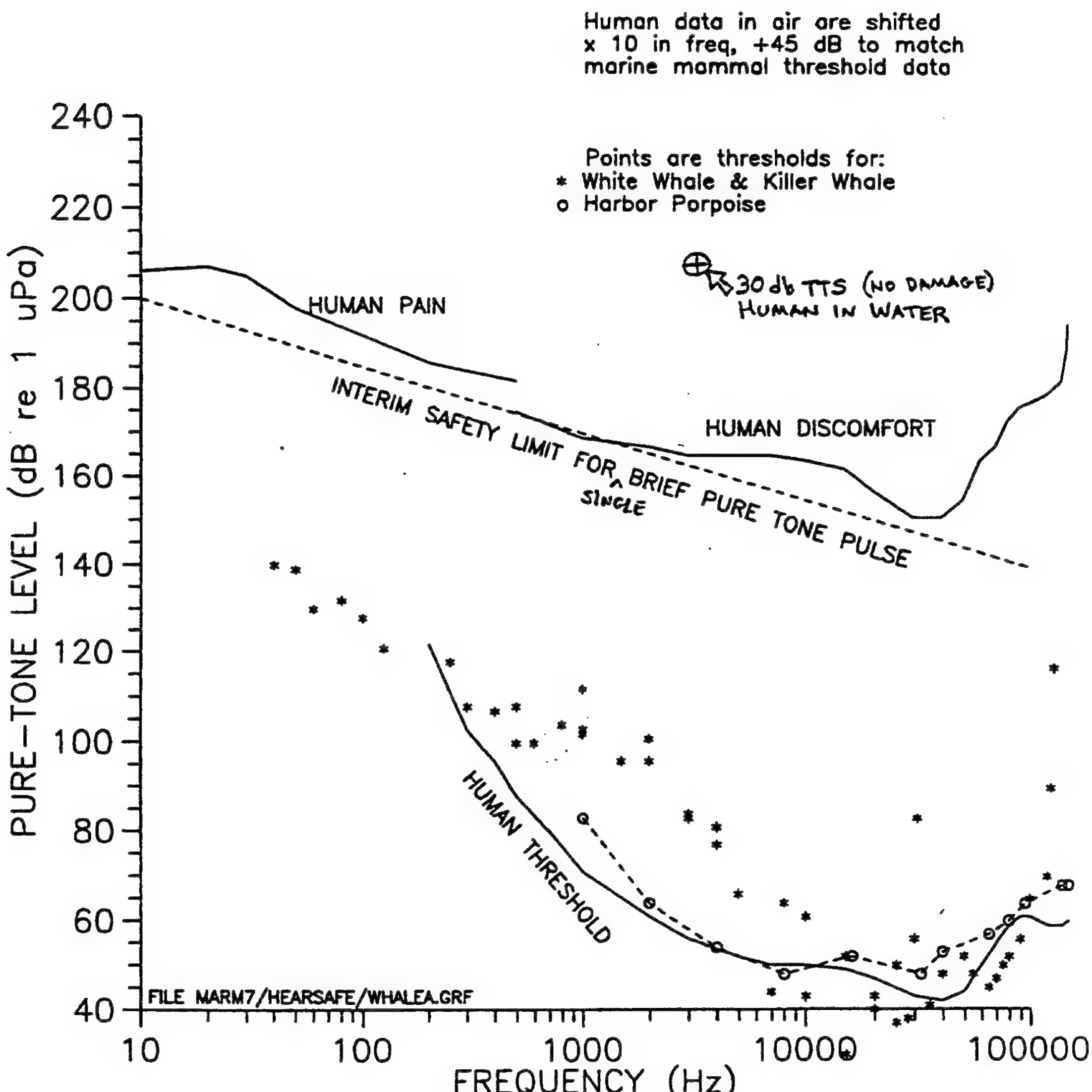


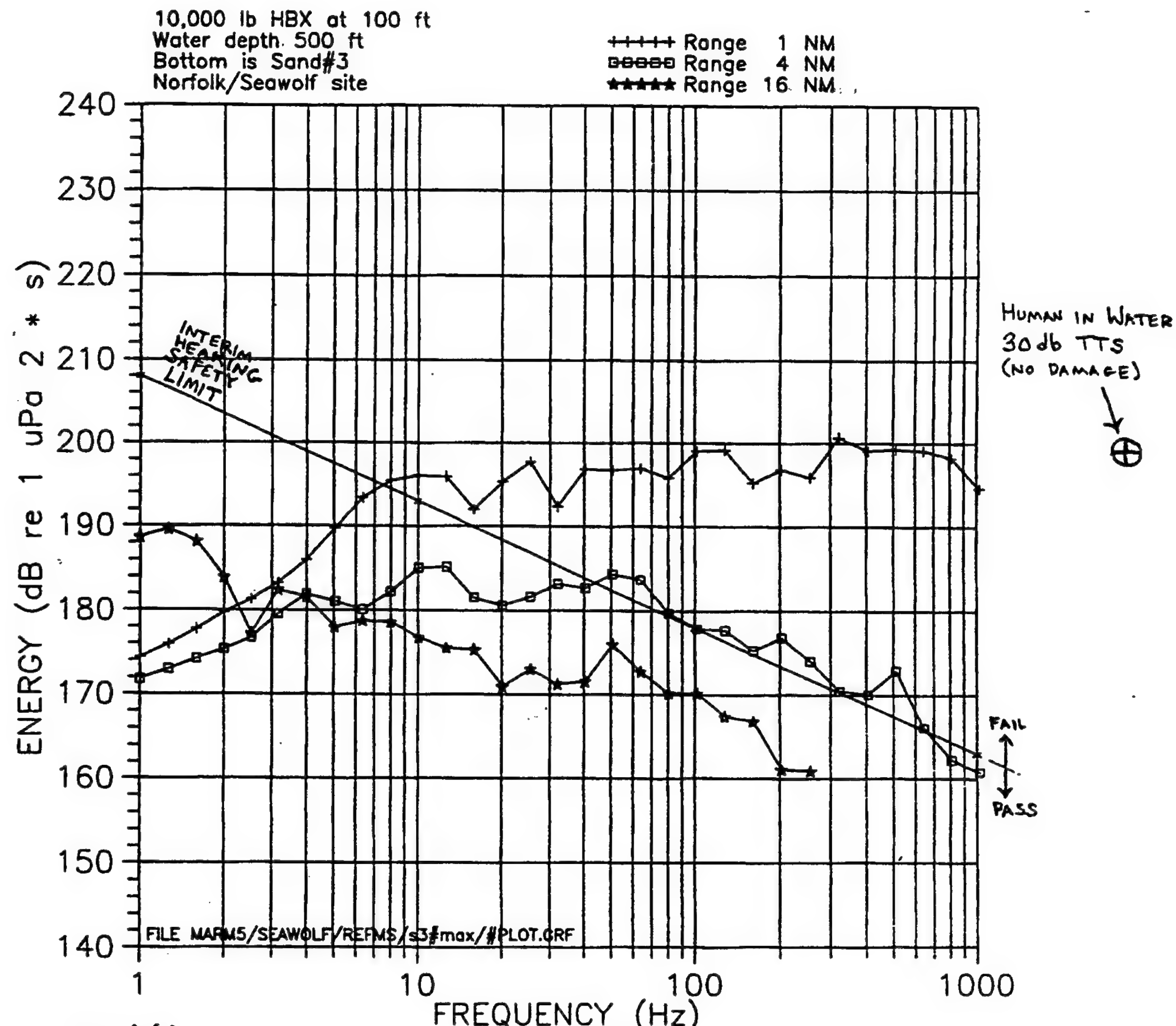
FIG. 1 - Equal-loudness contours of the human ear in air of Ref (3) [ENCL. (b)]



of Ref (2)

Fig. 2 — Interim Marine Mammal Hearing Safety Limit for Brief Pure Tones Based on Shifted Human Data in Air

ENCL, (c)



of Ref (2)

Fig. 3 – Example of Application of Hearing Safety Limit

ENCL. (d)

APPENDIX E

CALCULATIONS FOR SELECTED ARCHIVAL PROFILES FROM THE PROPOSED SEAWOLF TEST AREAS

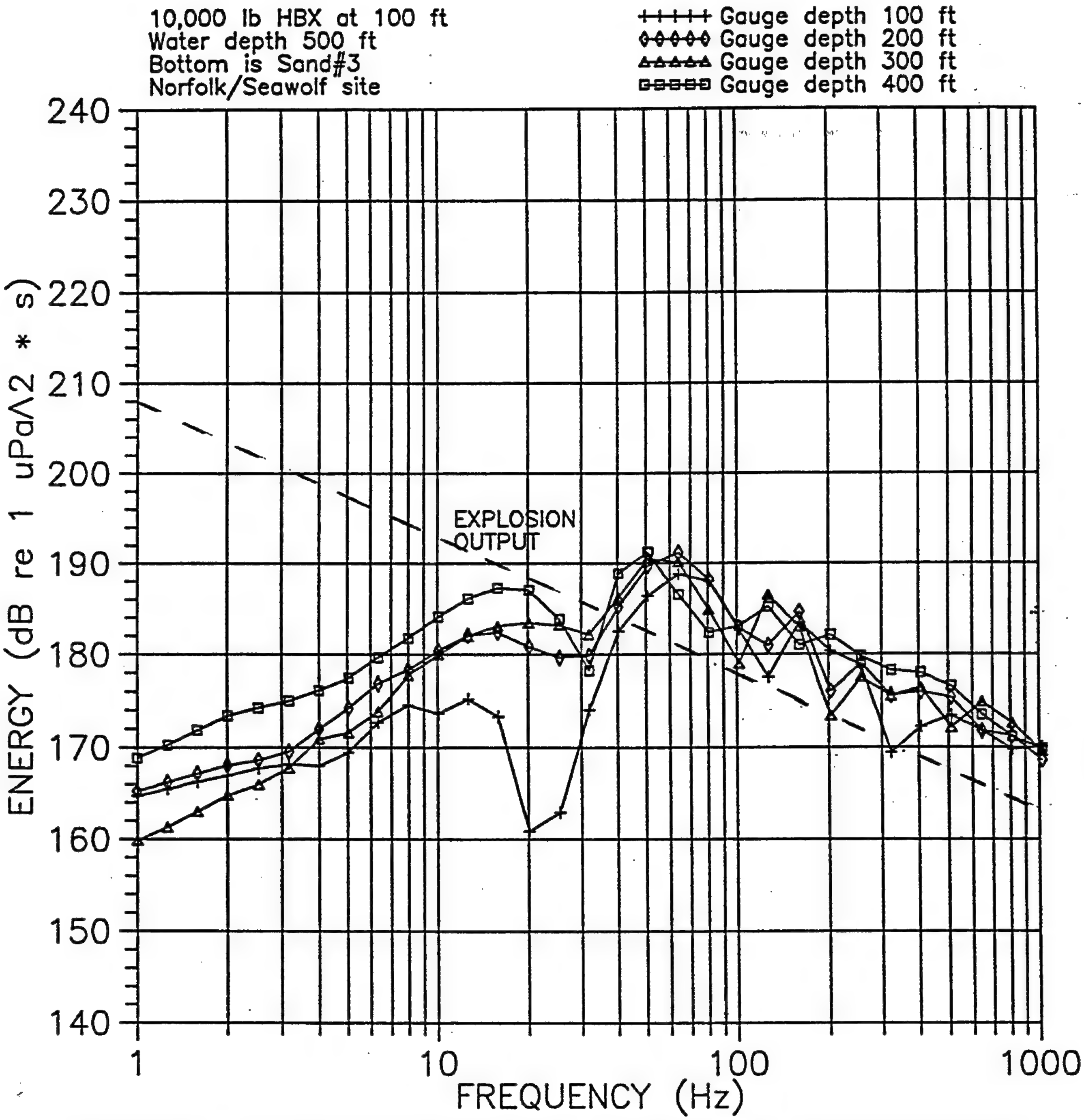


FIGURE E-1. 1/3-OCTAVE-BAND ENERGY VS FREQUENCY - NORFOLK AREA: APRIL; RANGE = 4 NM; MAMMAL DEPTH = 100 TO 400 FT

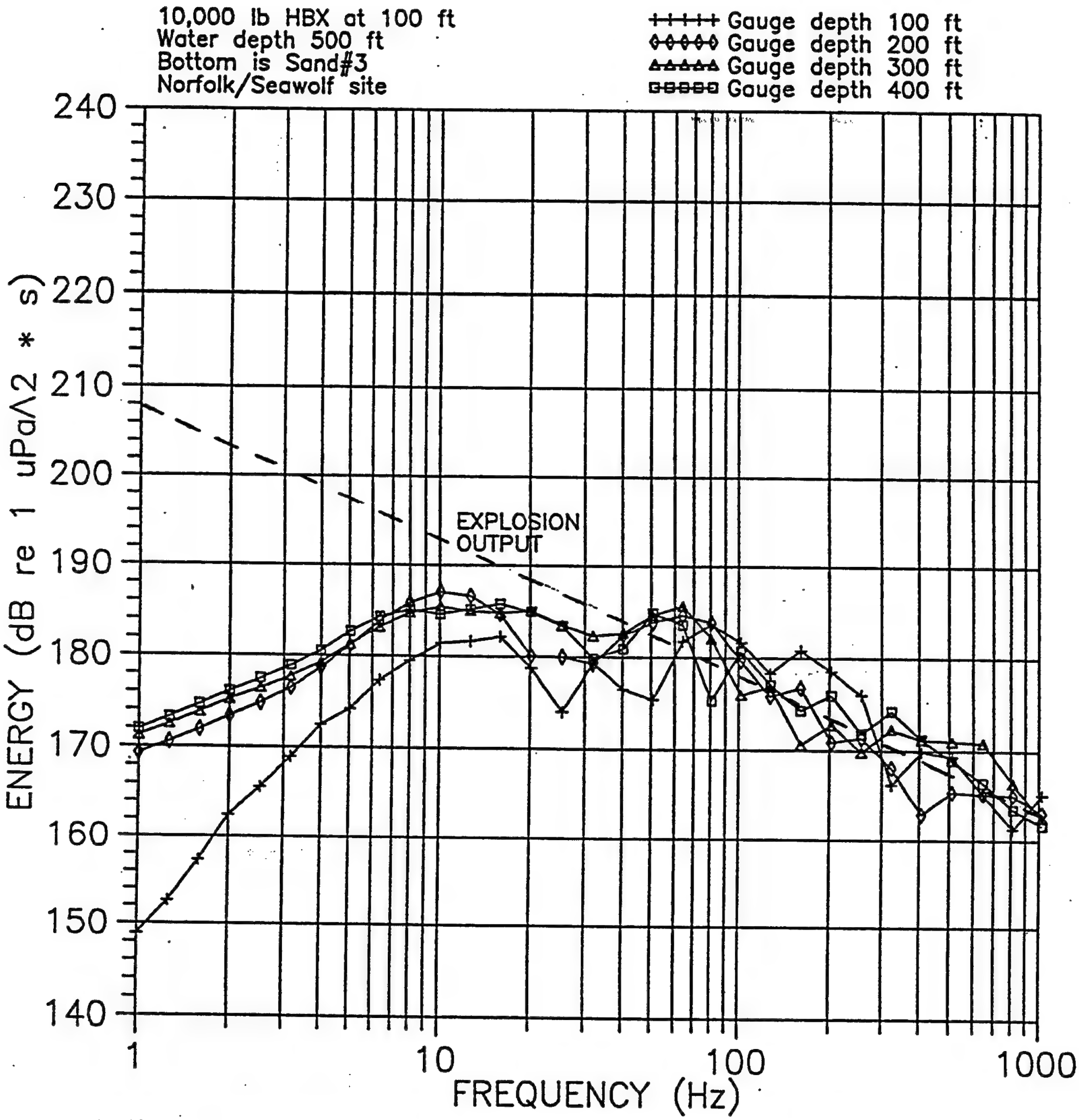


FIGURE E-2. 1/3-OCTAVE-BAND ENERGY VS FREQUENCY - NORFOLK AREA
APRIL; RANGE = 6 NM; MAMMAL DEPTH = 100 TO 400 FT

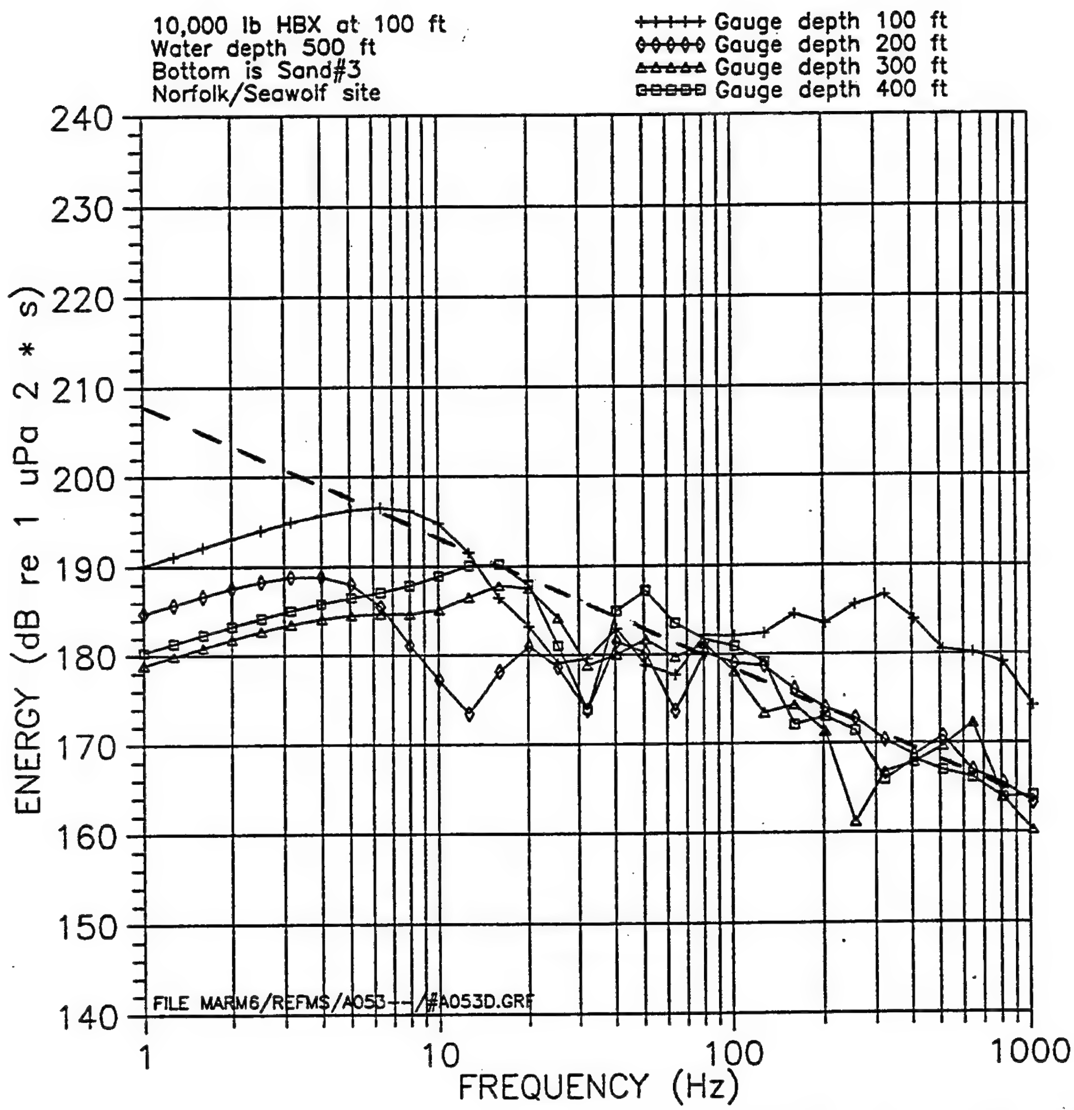


FIGURE E-3. 1/3-OCTAVE-BAND ENERGY VS FREQUENCY - NORFOLK AREA
MAY-EARLY JUNE; RANGE = 4 NM; MAMMAL DEPTH = 100 TO 400 FT

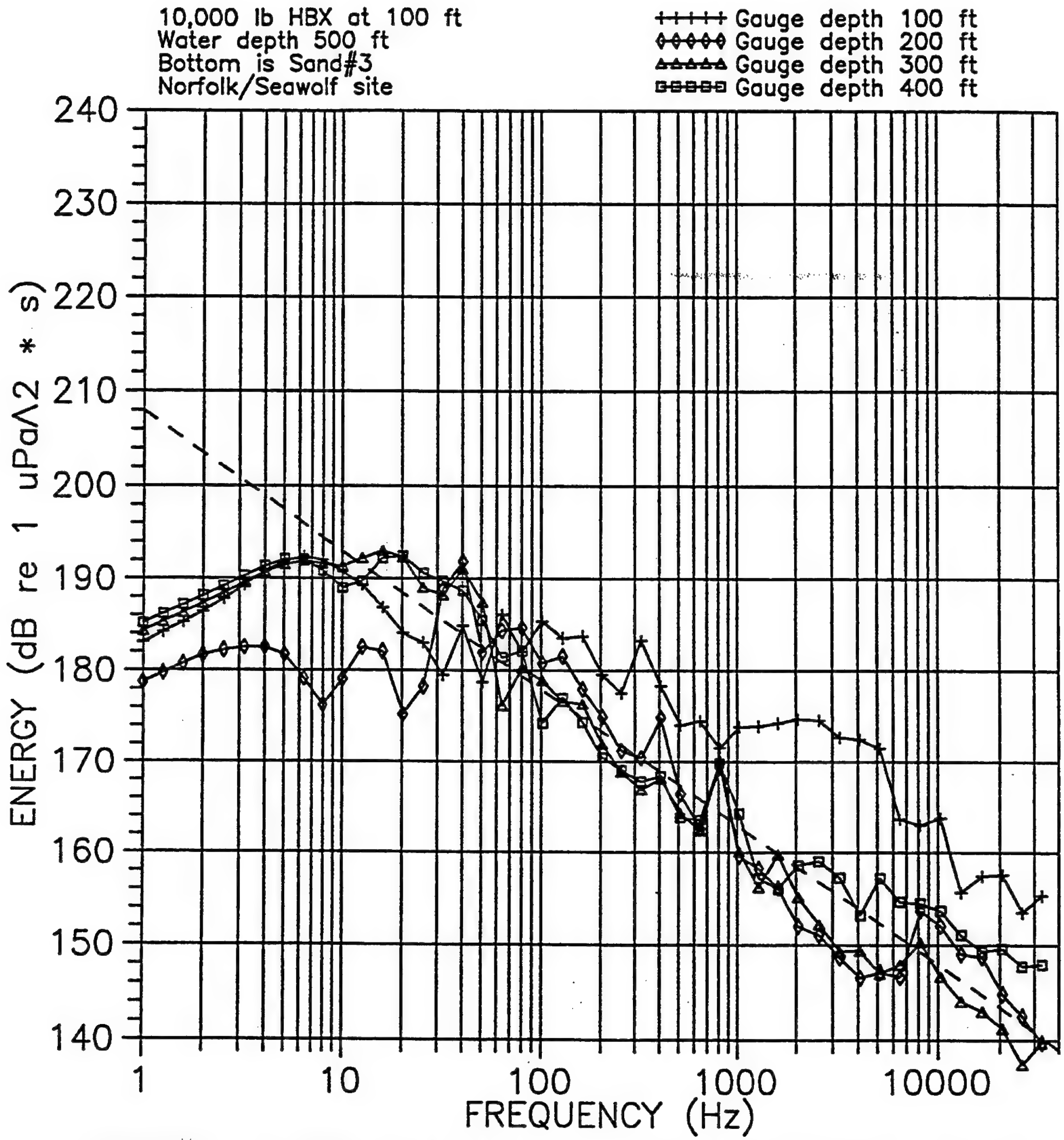


FIGURE E-4. 1/3-OCTAVE-BAND ENERGY VS FREQUENCY - NORFOLK AREA
LATE JUNE-EARLY JULY; RANGE = 4 NM; MAMMAL DEPTH = 100 TO 400 FT

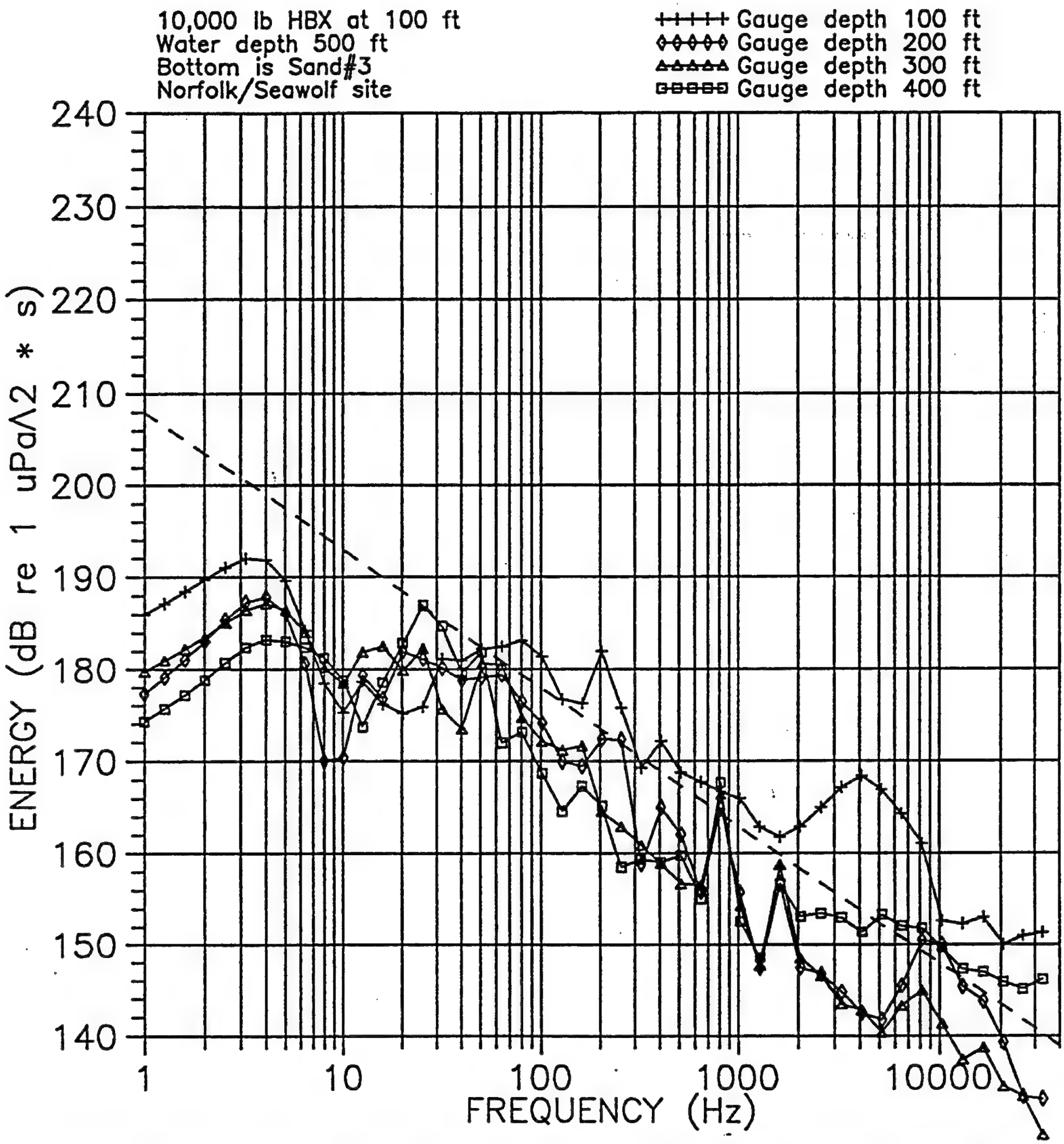


FIGURE E-5. 1/3-OCTAVE-BAND ENERGY VS FREQUENCY - NORFOLK AREA
LATE JUNE-EARLY JULY; RANGE = 6 NM; MAMMAL DEPTH = 100 TO 400 FT

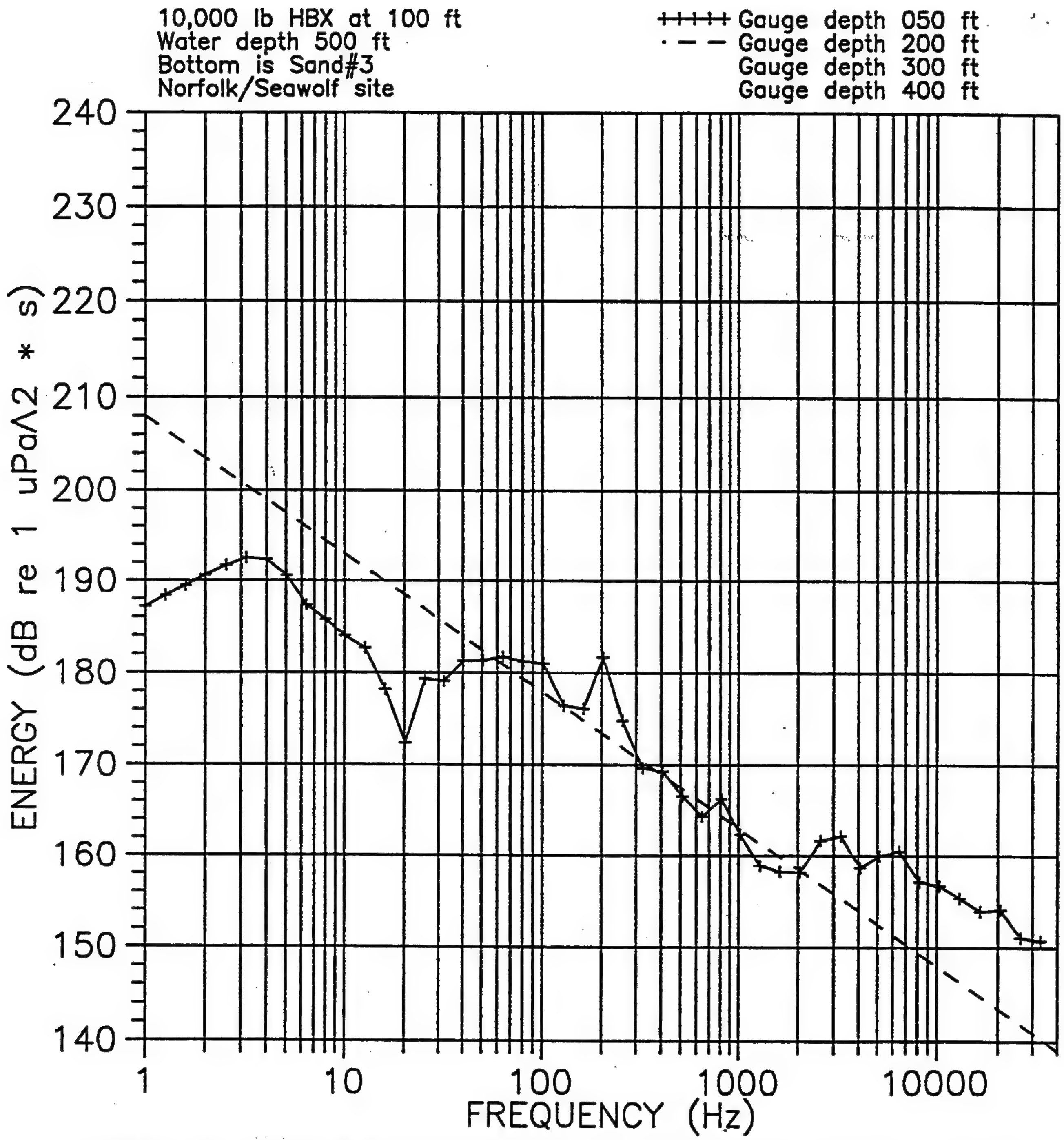


FIGURE E-6. 1/3-OCTAVE-BAND ENERGY VS FREQUENCY - NORFOLK AREA
LATE JUNE-EARLY JULY; RANGE = 6 NM; MAMMAL DEPTH = 50 FT

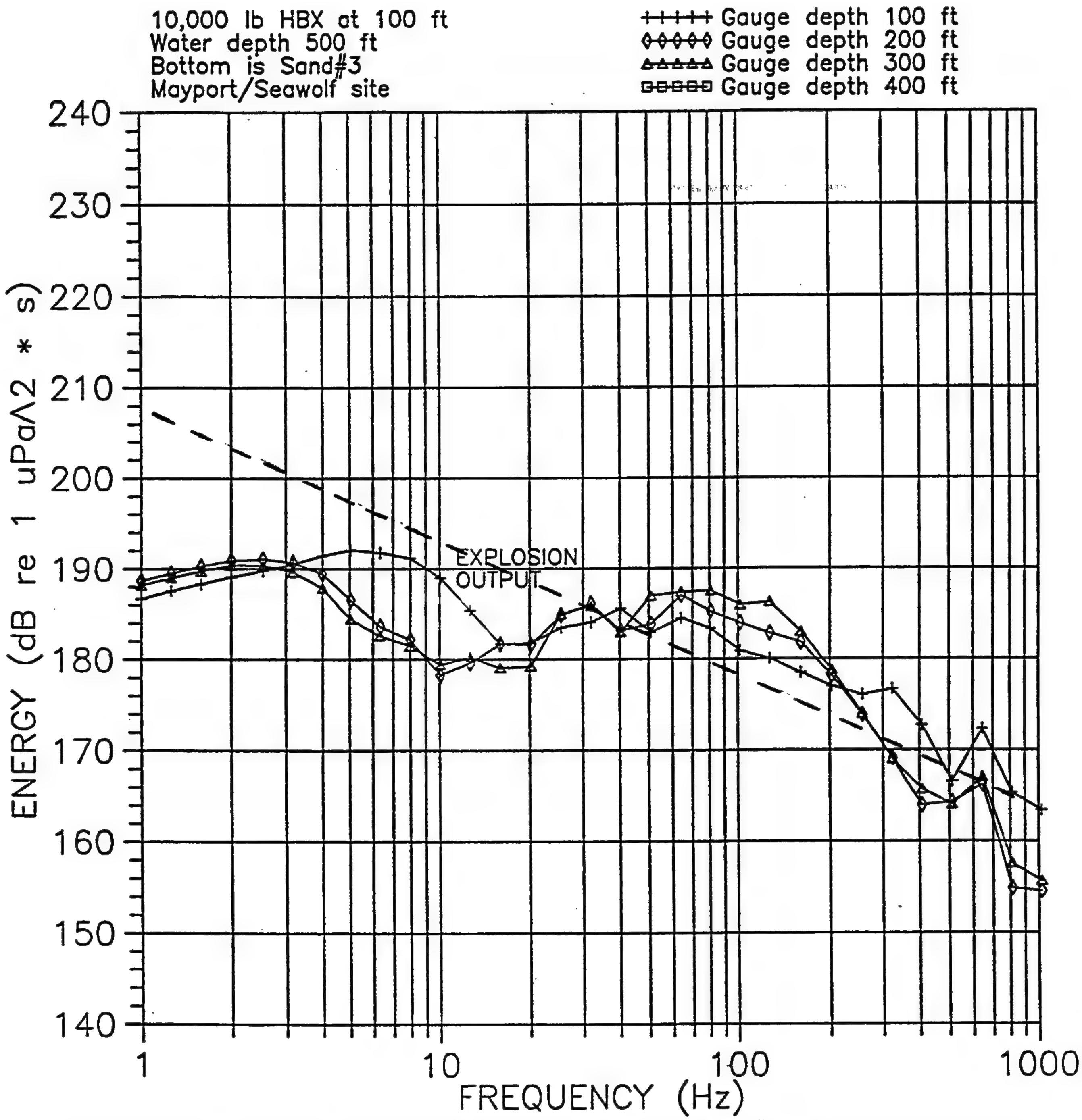


FIGURE E-7. 1/3-OCTAVE-BAND ENERGY VS FREQUENCY - MAYPORT AREA
APRIL-MAY; RANGE = 4 NM; MAMMAL DEPTH = 100 TO 400 FT

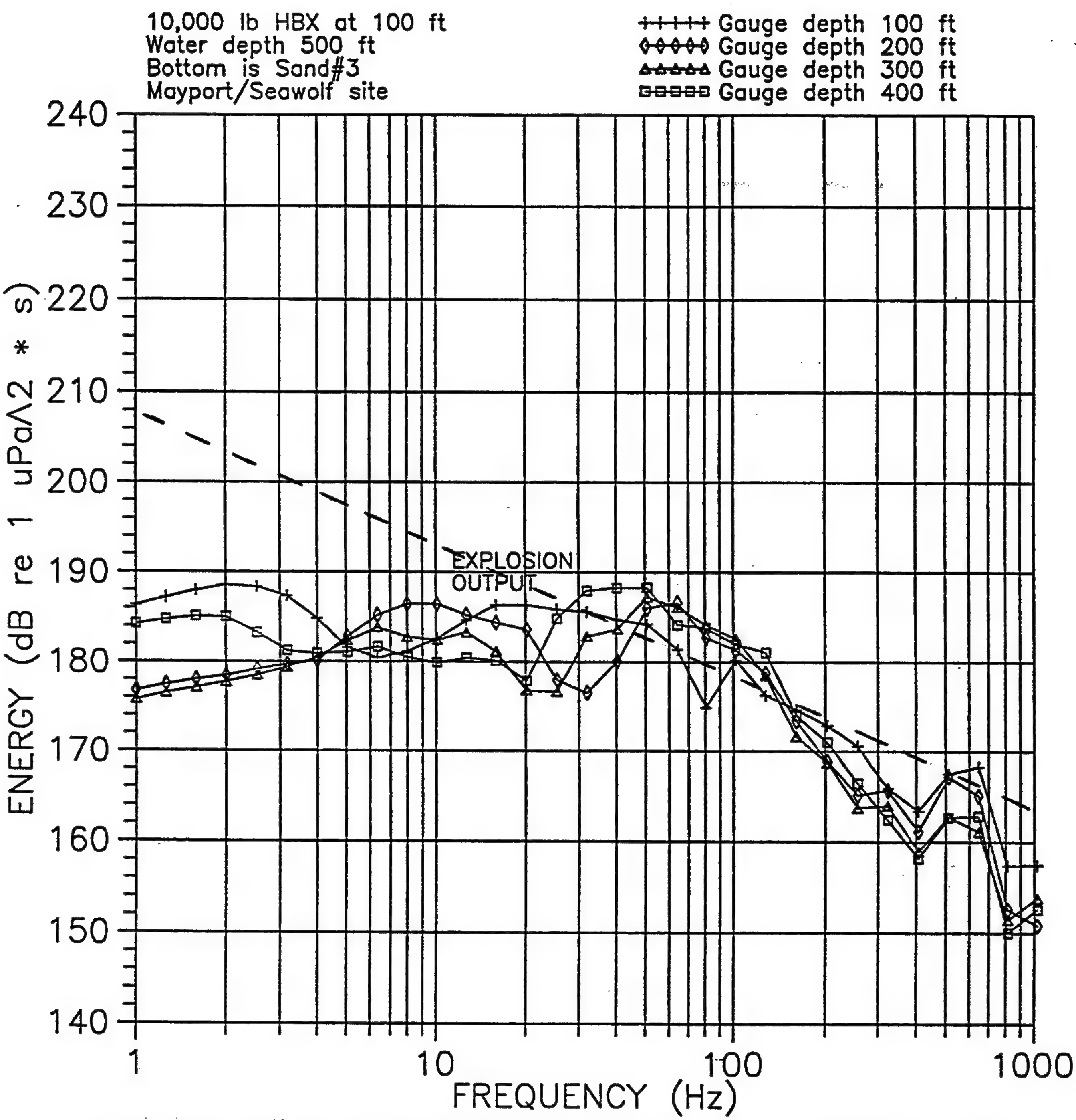


FIGURE E-8. 1/3-OCTAVE-BAND ENERGY VS FREQUENCY - MAYPORT AREA
APRIL-MAY; RANGE = 6 NM; MAMMAL DEPTH =: 100 TO 400 FT

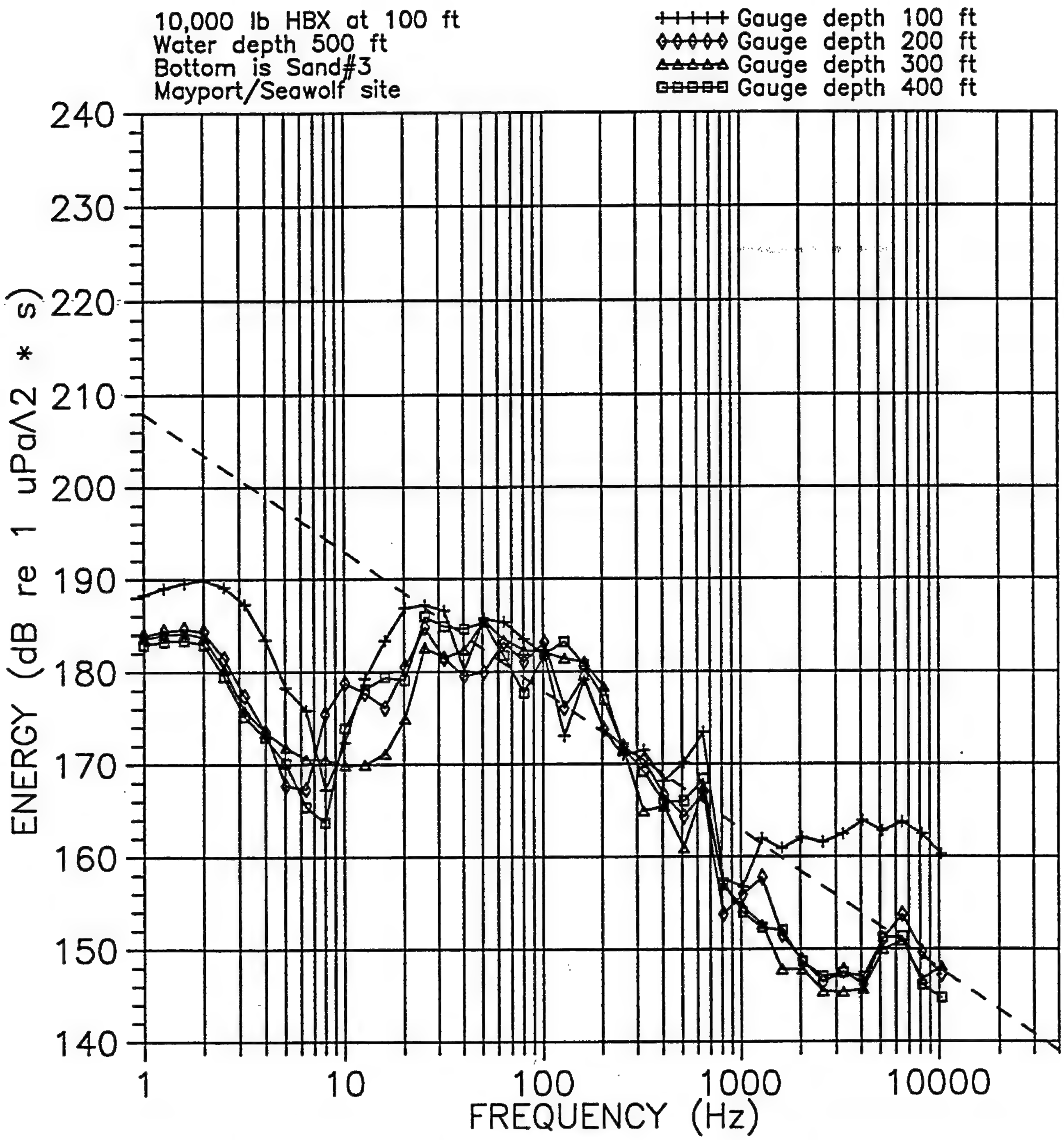


FIGURE E-9. 1/3-OCTAVE-BAND ENERGY VS FREQUENCY - MAYPORT AREA
JUNE-JULY; RANGE = 4 NM; MAMMAL DEPTH = 100 TO 400 FT

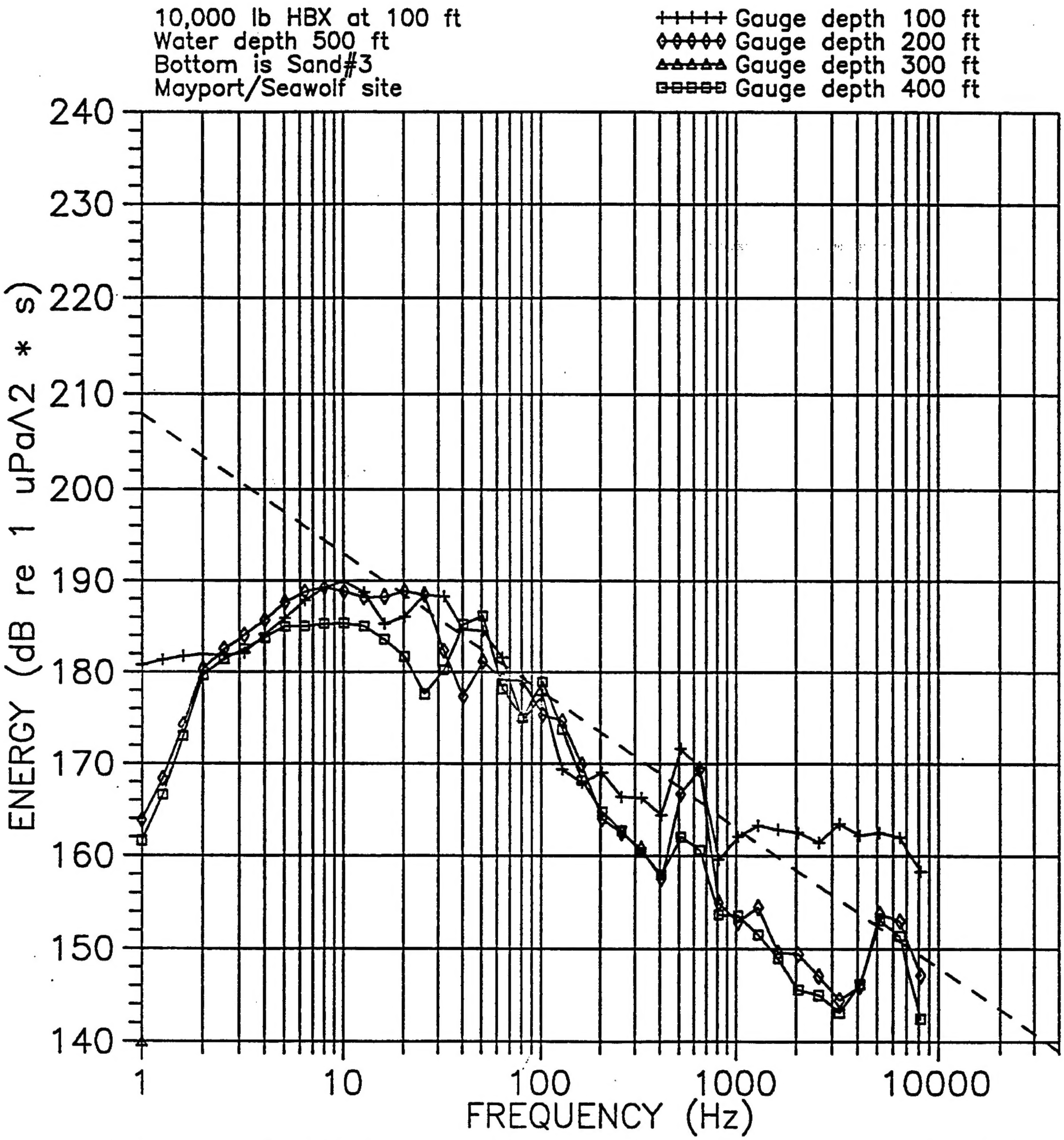


FIGURE E-10. 1/3-OCTAVE-BAND ENERGY VS FREQUENCY - MAYPORT AREA
JUNE-JULY; RANGE = 6 NM; MAMMAL DEPTH = 100 TO 400 FT

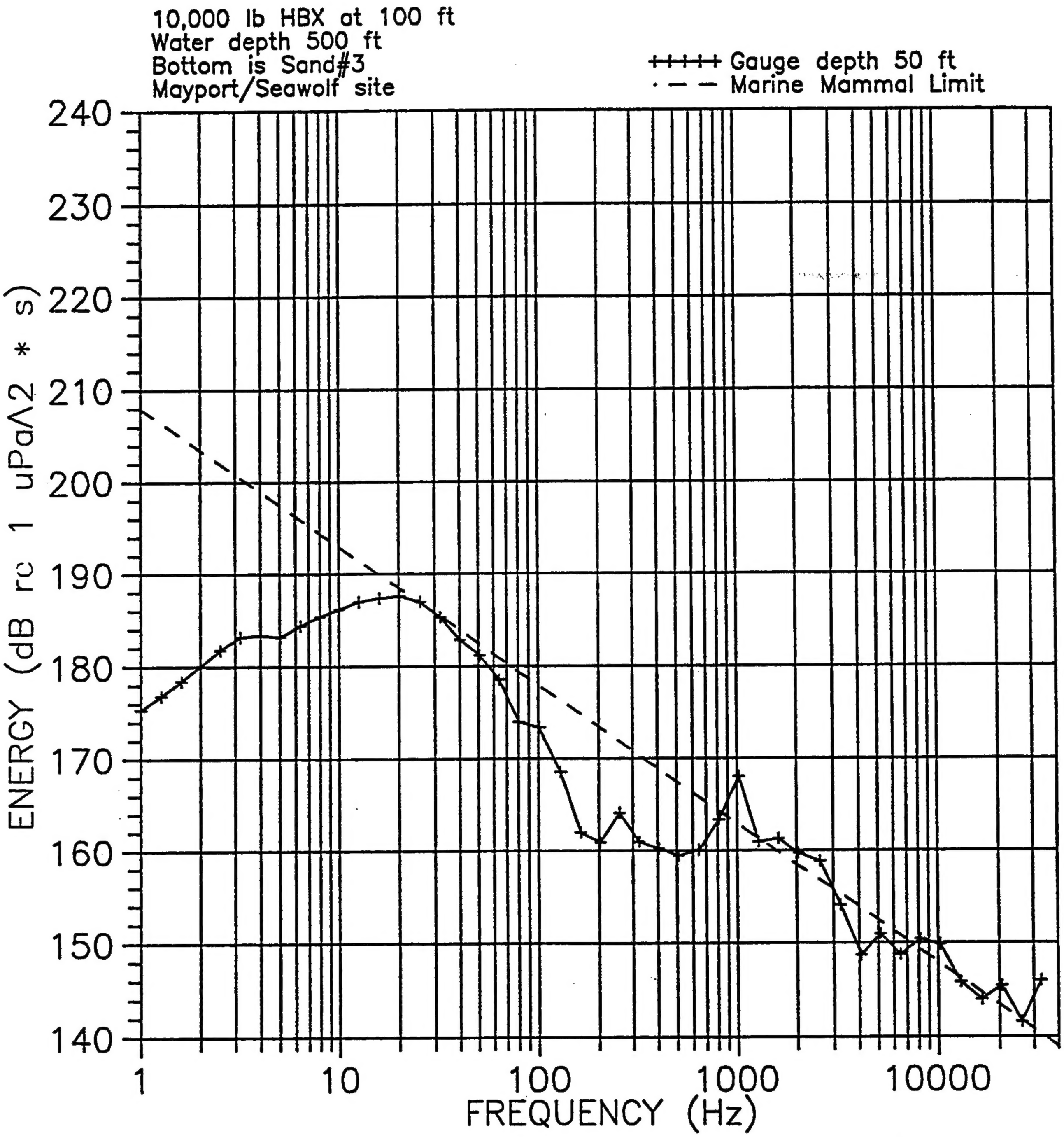


FIGURE E-11. 1/3-OCTAVE-BAND ENERGY VS FREQUENCY - MAYPORT AREA
JUNE-JULY; RANGE = 6 NM; MAMMAL DEPTH = 50 FT

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